



**National Aeronautics and
Space Administration**

**Exploration Systems
Interim Strategy**



The NASA Vision

To improve life here,
To extend life to there,
To find life beyond.

The NASA Mission

To understand and protect our home planet,
To explore the universe and search for life,
To inspire the next generation of explorers
... as only NASA can.

A Message from the Associate Administrator for Exploration Systems

August 2004

Dear Colleagues and Friends:

The Exploration Systems Mission Directorate is a new organization within NASA dedicated to creating a constellation of new capabilities, supporting technologies, and foundational research that enables sustained and affordable human and robotic exploration.

Our strategy for creating these new capabilities, supporting technologies, and foundational research flows from four overarching principles. Those principles are:



Corporate Focus

- Advancing the Vision for Space Exploration in tandem with NASA's Aeronautics Research, Science, and Space Operations Mission Directorates



Focused, Prioritized Requirements

- Targeted to demonstrate sustainable and affordable success in human and robotic exploration



Spiral Transformation

- Developing capabilities in stages (spirals) with evolving, modular components
- Maturing technologies for inclusion in future spirals—research and technology that will transform spirals without placing program execution at risk



Management Rigor

- Emphasizing time-phased priorities, cost performance, and personnel development
- Supported by a sound acquisition strategy that promotes innovation

Based on these principles, we derive specific program tasks targeted to build new capabilities, and engage in essential research and development. This process of flowing from our strategy to program tasks is iterative. Like our overall efforts, the strategy-to-task process is spiral in nature in that, through repeated analysis of costs, performance options, trends, and results—including progress in developing specific capabilities and progress in maturing essential technologies—we spiral towards the deployment of new, transformational capabilities in a manner that is effective and affordable.

Specific capabilities and supporting research and technology development will evolve over time. Presently, our organization has been tasked with developing a Crew Exploration Vehicle that will be used by astronauts to travel in space. We are also developing nuclear technologies that will enable long-duration space travel and evaluating plans for a new capability that may service, repair, and eventually de-orbit the Hubble Space Telescope. We are conducting research to ensure the health and safety of astronauts during long-duration space exploration far from Earth. We are actively engaged in promoting new approaches that will substantially involve industry and universities in these efforts. Our Centennial Challenges Program, which offers prizes to stimulate innovation, is one example of a novel approach.

We are now in the process of melding our programs with those previously managed by NASA's Office of Biological and Physical Research, including research and development efforts focused on crew health and life-support systems, countermeasures, and radiation protection. By merging our organizations, we will work together to address strategic technical challenges and minimize the health and safety risks for the crew of any space vehicle. Also, the Agency will be developing an updated Agencywide Strategic Plan. We will update our plans as our organization matures.

Craig Steidle

Associate Administrator for Exploration Systems



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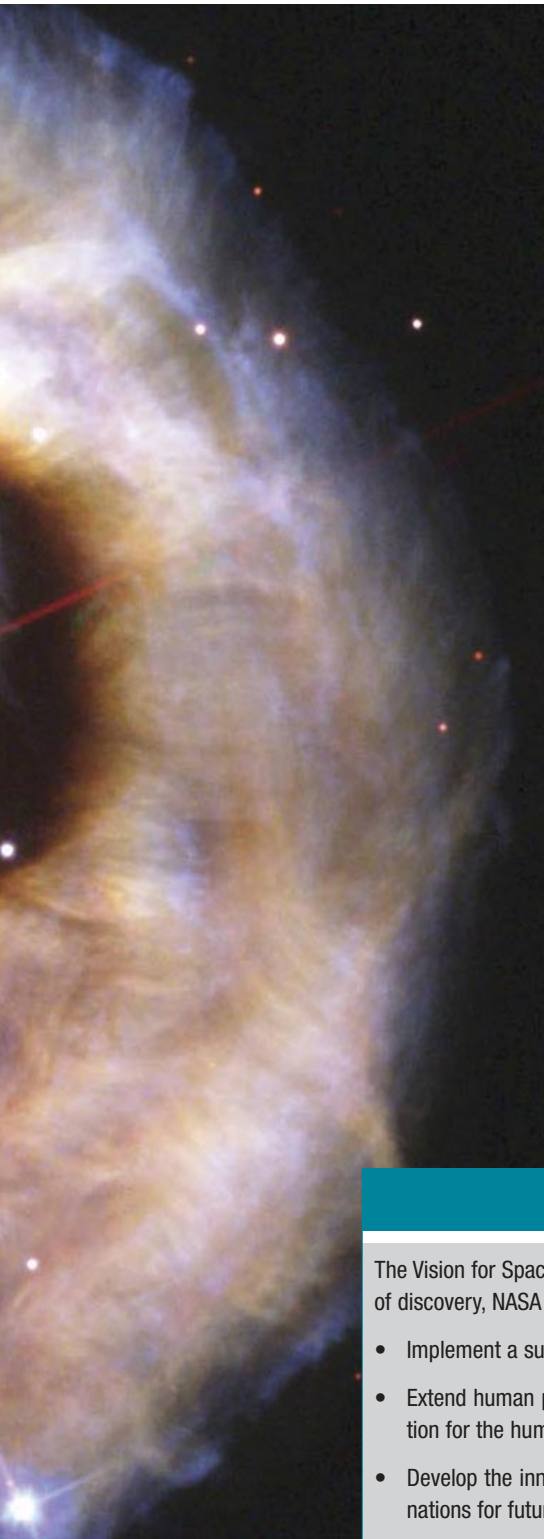


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**The Exploration
Systems Mission
Directorate
within NASA**



A burst of light from the star V838
Monocerotis spreads into space,
reflecting on surrounding shells of dust
to reveal a spectacular bull's eye.



1 The Exploration Systems Mission Directorate within NASA

Enabling the Vision for Space Exploration

On January 14, 2004, the President directed NASA to embark on a robust space exploration program that will advance the Nation's scientific, security, and economic interests. This is the fundamental goal of the Vision for Space Exploration.

"This cause of exploration and discovery is not an option we choose; it is a desire written in the human heart."

—President George W. Bush

NASA's exploration program will catalyze new discovery and understanding, inspire the next generation of explorers, lead to peaceful exploration of the Solar System by many nations, spark commerce between Earth and space, invigorate America's high-technology industry, and benefit life on Earth.

The Exploration Systems Directorate is charged with a leadership role in enabling the Vision for Space Exploration. **The Directorate's activities, as described in this Strategy, are derived directly from the Vision for Space Exploration.**

The Vision for Space Exploration: Objectives

The Vision for Space Exploration defines a new U.S. space exploration policy. In support of this policy, through a renewed spirit of discovery, NASA will:

- Implement a sustained and affordable human and robotic program to explore the Solar System and beyond
- Extend human presence across the Solar System, starting with a human return to the Moon by the year 2020, in preparation for the human exploration of Mars and other destinations
- Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about destinations for future human exploration
- Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests



The Role of the Directorate

The role of the Exploration Systems Mission Directorate is to develop a constellation of new capabilities, supporting technologies, and foundational research that enables sustained and affordable human and robotic exploration.

Over time, we will develop many new capabilities. Our Directorate will also invest in the maturation of technologies that will be incorporated within capabilities as the exploration agenda evolves. We will do this in a sustainable manner through ongoing, cost-effective performance that evidences success and evolutionary progress. To reduce risks and demonstrate performance, we will use the International Space Station (ISS) as an essential platform for conducting research and testing new technologies.

The capabilities and technologies we develop will evolve over time, based on NASA's exploration goals, budgetary priorities, trade studies,

and other analyses of costs, benefits, and risks. This evolution will take place in stages or "spirals" that will allow NASA to respond flexibly to new scientific discoveries and incorporate new technologies, while minimizing risk and avoiding costly redesign.

Over time we will deploy a set of systems, large and small, that will be integrated into a "system-of-systems." This includes Earth-to-orbit

and in-space transportation systems, systems required for human health and performance, as well as robotic systems that will assist humans as they travel and explore. For these systems, NASA may rely on existing in-space systems and supporting infrastructure or choose to enhance or replace existing infrastructure or systems.

The capabilities we create will allow NASA to extend, in an affordable and sustainable manner, human presence beyond low Earth orbit (LEO) to the Moon, Mars, and beyond. On this journey, humans will return to the Moon to demonstrate their ability to live and work far from

Earth. Exploration, science, and discovery will occur on the Moon, and expeditions to the Moon will be tailored to reduce the risks associated with Mars exploration.

An anchoring capability will be a Crew Exploration Vehicle (CEV) that will carry human crews from Earth to space. When coupled with transfer stages, landing vehicles, and surface exploration systems, the CEV will serve as an essential component of an architecture that supports humans on voyages to the Moon and beyond.

To support the exploration needs of the Agency, our Directorate—working in close collaboration with other NASA Directorates—will be tasked to develop unique capabilities for specific scientific missions. These missions will be used to develop and demonstrate exploration capabilities, thereby advancing the exploration agenda, while supporting near-term science objectives. Examples include the possible development of the capability necessary to robotically repair the Hubble Space Telescope and the development of nuclear power and propulsion for a revolutionary robotic mission to study Jupiter's icy moons. This initiative, "Project Prometheus," would demonstrate the safe and reliable use of nuclear technologies in space, and further efforts toward the human exploration of the Moon, Mars, and beyond.

Each development spiral will support the Agency's overarching exploration agenda. This agenda is refined through exploration roadmaps established by the Agency, in coordination with all NASA Mission Directorates. For each spiral, the Exploration Systems Mission Directorate will be responsible for establishing clear, firm requirements and for promoting overall implementation, including integration across Directorates.

Along with tapping creative expertise from within the NASA organization, the Directorate will leverage ideas and expertise from industry and international participants, as well as academic and other government institutions. Through Centennial Challenges, we will establish competitions to stimulate innovation that can advance the exploration vision.

The Directorate's Primary Contributions to NASA Goals

- Explore research in the natural laboratory of space (goal 4)
- Extend the duration and boundaries of human space flight to create new opportunities for exploration and discovery (goal 9)
- Enable revolutionary capabilities through new technology (goal 10)

—From the NASA Strategic Plan (2003)



The Exploration Systems Mission Directorate: Our Culture

The Exploration Systems Mission Directorate is a new organization. Building on NASA's values, the organization we are creating will embody the following characteristics:

Safety: Each individual in our organization will be encouraged and empowered to advance safety and mission success. Recognizing that space flight is inherently risky, we will use all available resources to minimize the risk to human life while accomplishing mission objectives.

NASA Family: Our people are our most important resource. We are committed to mutual respect, personnel development, and nurturing transitions, in line with Agency transformations and "One NASA."

Excellence: In all that we do, we will strive for excellence. We will be practical, professional, flexible, and innovative.

Integrity: We will be credible in our words and performance. We will garner credibility for NASA by demonstrating cost-effective, in-space performance. This will catalyze further exploration on behalf of all humankind.

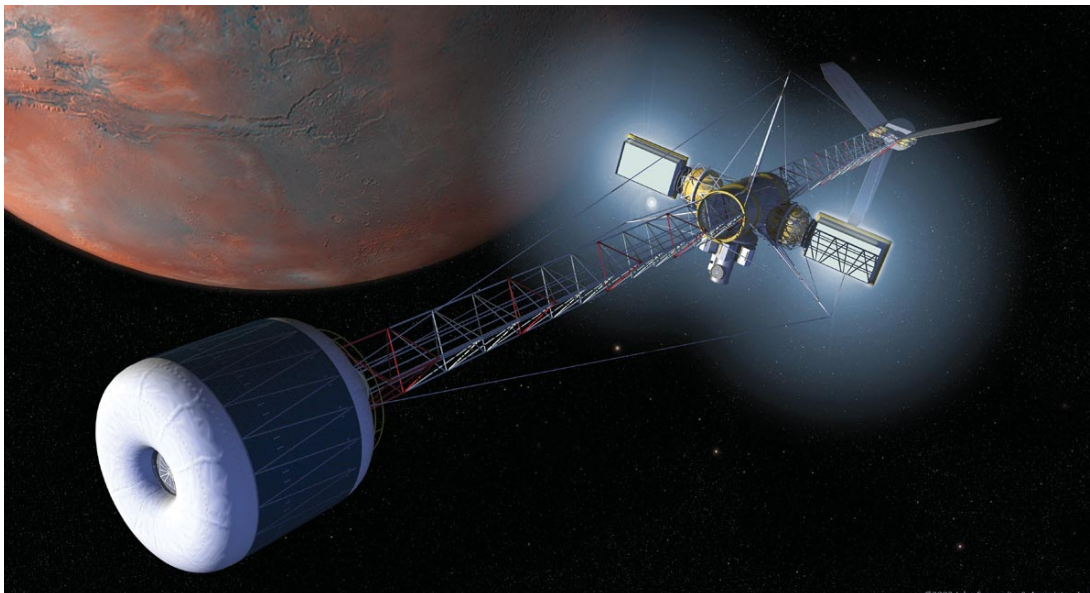
As our Directorate evolves, it will be nurtured within an atmosphere and culture that promotes open communication, particularly about issues affecting safety and mission success. In addition to rigorous engineering testing and safety analysis of all technologies and systems, each person associated with the Directorate, including our contractors and subcontractors, will be encouraged and empowered to promote safety and mission success in their day-to-day activities.

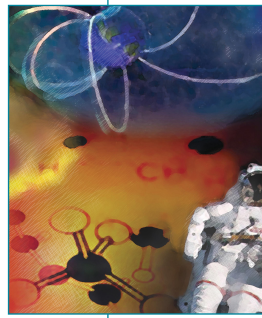
To meet our exploration responsibilities, the Directorate will invest in our people. We are committed to personnel development that nur-

tures individual growth. In return, all members of the Directorate are expected to maintain high standards of integrity in their work and conduct. We will treat others with the utmost respect. We will strive continually for excellence by being professional and practical, as well as flexible and innovative. We will be credible in our words and performance.

By demonstrating repeated in-space performance, our Directorate will establish itself as a credible, respected organization, and thereby foster sustained exploration on behalf of all Americans.

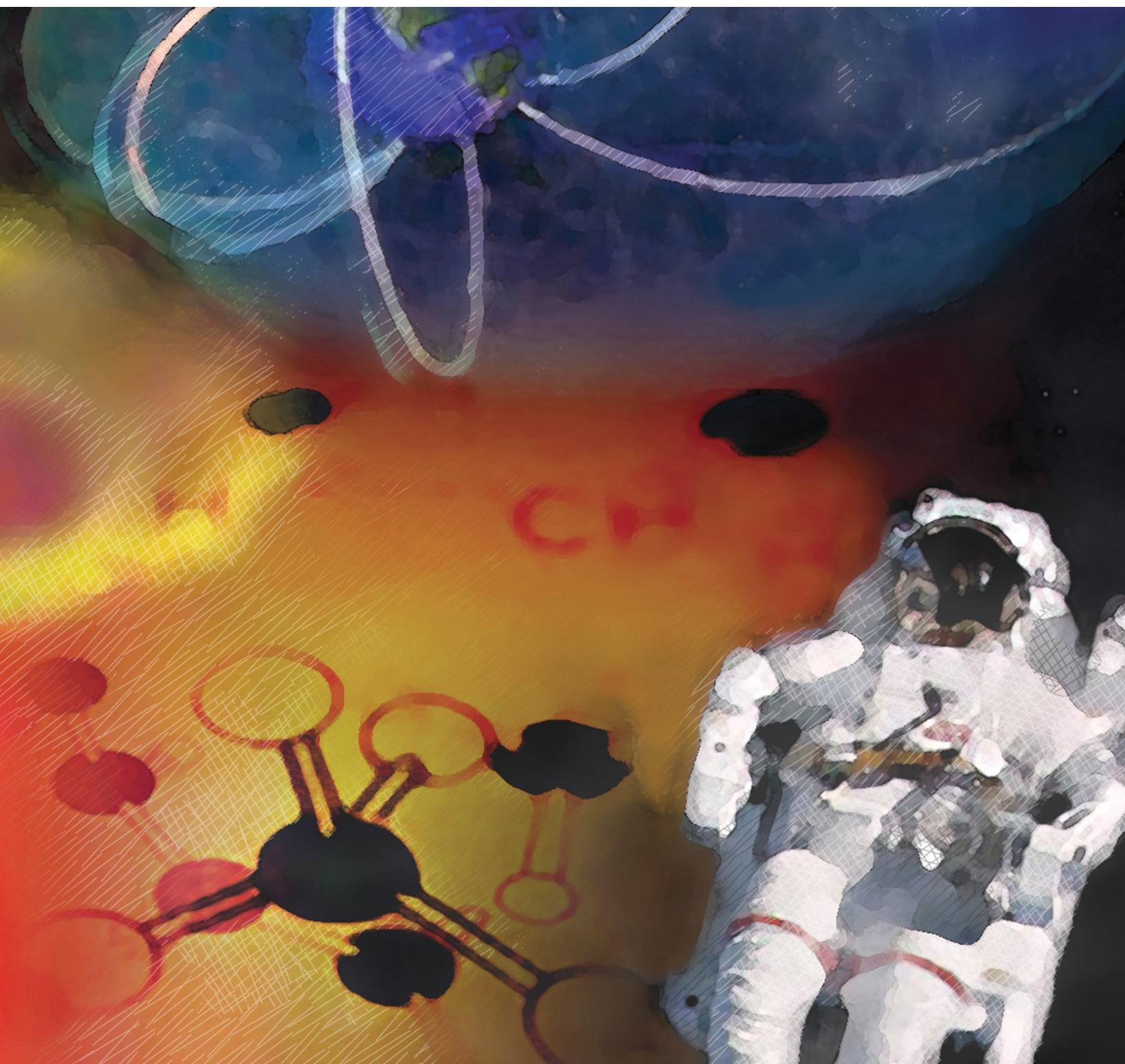
Mars artificial gravity transfer vehicle (artist's concept).





2

Strategic Context and Approach



2 Strategic Context and Approach

“Fortune favors the bold”

—Virgil

Building on the strengths of NASA, the Exploration Systems Mission Directorate will enable sustainable and affordable success in human and robotic exploration. Four overarching principles define our strategic approach:



Corporate Focus

We are a cohesive organization with a common focus. Our common focus is to advance the Vision for Space Exploration. We do this in partnership with the Aeronautics Research, Science, and Space Operations Mission Directorates. We advance overarching goals by integrating complex work from multiple organizations. We welcome contributions from all sources and rely on those organizations best able to perform.



Focused, Prioritized Requirements

We involve users, operators, researchers, and technologists to craft focused, prioritized requirements for new capabilities. These requirements will be based on realistic parameters for cost, schedule, and performance. We use sound risk reduction methods to promote safety and mission success. We will not allow for “requirements creep.” Once established, requirements will be rigorously controlled.



Spiral Transformation

We develop new capabilities in stages or “spirals” with evolving modular components. In this way we can respond to new opportunities without costly redesign. To lower costs and improve performance, we invest in technology innovation in a manner that can transform future spirals without placing program execution at risk.



Management Rigor

We are disciplined managers. We establish time-phase priorities, apply risk-management principles, ensure performance within budget, and nurture personnel development. Our management approach is supported by a sound acquisition strategy that promotes success and innovation.

A mosaic portraying humans in the space environment (artist's concept).





Science

EXPLORATION SYSTEMS

Education and Outreach

Aeronautics Research

Flight Operations



Corporate Focus

Advance the Vision for Space Exploration

The Exploration Systems Mission Directorate strives to advance the Vision for Space Exploration. All of our programs will work together to enable NASA's exploration agenda.

We will strive to eliminate bureaucratic barriers and create synergy. From requirements to research, our programs will reinforce each other and work together to address essential systemic issues.

For example, our Advanced Space Technology Program will issue a Broad Agency Announcement (BAA) seeking to support cutting-edge, peer-reviewed research that will demonstrate the viability of a particular approach. Awards will be issued to teams led by industry, universities, or NASA Centers. Similarly, our Small Business Innovation Research Program (SBIR) will fund innovative research by small businesses. Our Centennial Challenges Program will offer a prize to any organization able to provide an innovative solution to a specified research goal. Our Human System Research efforts will provide solutions for crew health, safety, and productivity in deep space. On the basis of the combined efforts of all of our research programs, our Technology Maturation Program will invest in the most advanced methodologies for in-space testing and deployment. When a system is sufficiently mature, our Requirements Division will establish key performance parameters and the new system will be incorporated into mission plans in the most beneficial way possible.

All of our efforts are interrelated. Engineers, scientists, operators, planners and business professionals from all divisions within our Directorate will examine the feasibility of a new technology system and its interoperability with other systems. If the new system fits our requirements and offers improvements over the status quo, it will be used. If it remains a promising area, but is not yet ready for in-space operations, our researchers and operators will work together to identify and effect improvements.

We do not make system-level decisions in a vacuum. Rather, we will use a simple benchmark: To what degree does each decision advance NASA's overarching goals? To reinforce this behavior, key decisions, including contracting, will be made at the highest organizational level based on their potential to advance overarching goals.

Evaluate and Transform Existing Programs

In order to ensure that we are using our resources wisely, we continually evaluate and assess the effectiveness of our programs. This process is essential and takes judgment and introspection. If programs effectively further exploration goals, they are given clearance to continue to the next milestone. If they provide us with important exploration capabilities, but are not fully positioned to fulfill our organizational requirements, we will retool and transform them.

Some existing programs may not be successful or may not be well-focused on the tasks assigned to our Directorate. After careful consideration, we may transfer programs to other Directorates or discontinue them as appropriate.

Advance "One NASA" with Other NASA Organizations

The Exploration Systems Mission Directorate will not accomplish our tasks alone. We further the concept of "One NASA" by working closely with all other NASA organizations. Together we will provide the greatest value to the Nation and make the most of our resources.

To foster deep cooperation, we employ active liaisons who work to maximize discourse and minimize barriers between our organization, the other NASA Directorates, and the NASA Field Centers.

Transformation

We will operate as "One NASA" in pursuit of our Vision and Mission.

NASA is a large agency, consisting of thousands of public servant and contractor employees, Field Centers across the United States, and facilities in foreign countries. With our new focus on a unified long-range Vision and Mission, it is imperative that all elements of the Agency work together as a single team.

—From the NASA Strategic Plan (2003)



Coordinating with experts from other parts of the Agency allows us to implement Agencywide practices that promote safety and mission success, including methods of risk management.

Rely on NASA Centers, Industry, Universities, Other U.S. Government Agencies, and International Participants

In amassing the capabilities necessary to implement the Vision for Space Exploration, we will be open to all capable sources. We will draw on a

diverse pool of organizations to discover innovative practices and promote synergy.

Organizations that work with us must be able to perform. Our focus will be on finding the best organization or team of organizations to fulfill each requirement.

We will rely on a portfolio of talent from NASA Centers, as well as other U.S. government agencies, industry, and universities. We will actively strive to include international participants as well.

International Participation

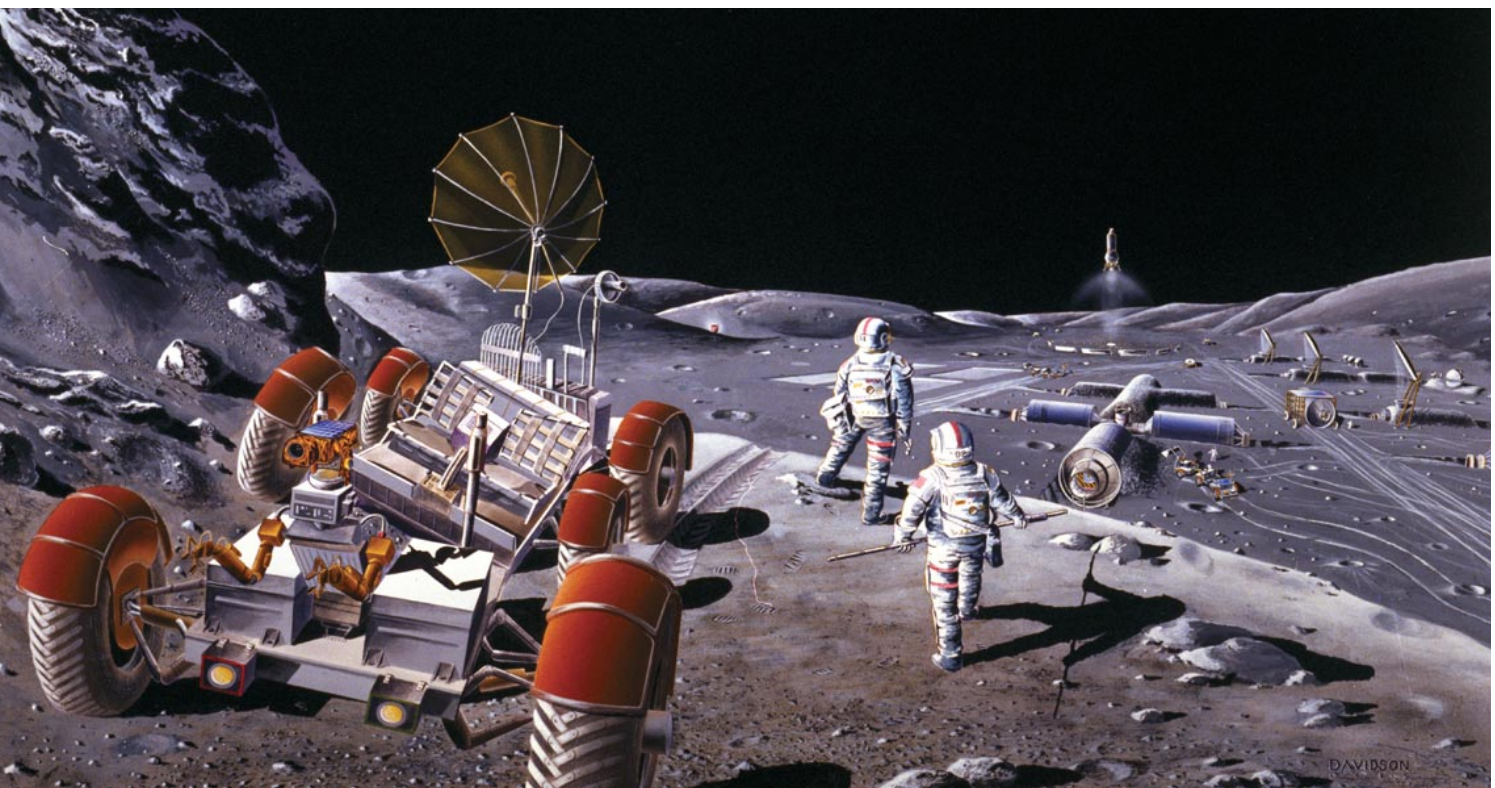
In accordance with the Vision for Space Exploration, our Directorate will pursue opportunities for international participation. We can benefit greatly from the industry and creativity of other nations. We will draw from our long history and close ties with the space and research agencies of other nations. We will actively seek opportunities by entering into discussions with potential international collaborators to identify capabilities and technologies that would add value, avoid unnecessary duplication, and maximize the chance of success in implementing the Vision for Space Exploration.

International participation is vital for human and robotic space exploration. When we return to the Moon, we will again come “in peace for all mankind.”

We remain committed to the International Space Station to test and demonstrate new technologies, perform research, and reduce the risks associated with future space travel. Here, too, our international partners play a crucial role.

Like any human endeavor, we are defined both by our will and by our ability. We will work with all who have the will and ability to advance humankind’s exploration goals.

Lunar base (artist’s concept).



Providing and Receiving Support

Our relationship with other organizations is interactive. The services we receive from those organizations and the services we provide to other organizations are listed in the following charts:

Service	Received from:						
	NASA Science	NASA Space Operations	NASA Aeronautics	NASA Education	Other Government Agencies	International Partners	Industry
Scientific Requirements	•						•
Robotic Demonstration Missions	•	•	•			•	•
Research & Technology Development	•	•	•		•	•	•
Nuclear Technology Research					•		•
Launch Services		•					•
Space Communications		•				•	•
International Space Station Research Platform		•				•	•
Education & Outreach				•			•

Service	Provided to:						
	NASA Science	NASA Space Operations	NASA Aeronautics	NASA Education	Other Government Agencies	International Partners	Industry
Exploration Systems Requirements	•	•	•		•	•	•
Exploration Systems Integration	•	•			•	•	•
New Capabilities	•	•			•	•	•
Research & Technology Development	•	•	•	•	•	•	•
Human Health and Performance Research	•	•		•	•	•	•
Nuclear Technology Research	•			•	•		•





Mission Commander Eileen M. Collins on Columbia's flight deck (top). Flight controller supports Space Shuttle operations (above).

Coordination and Integration

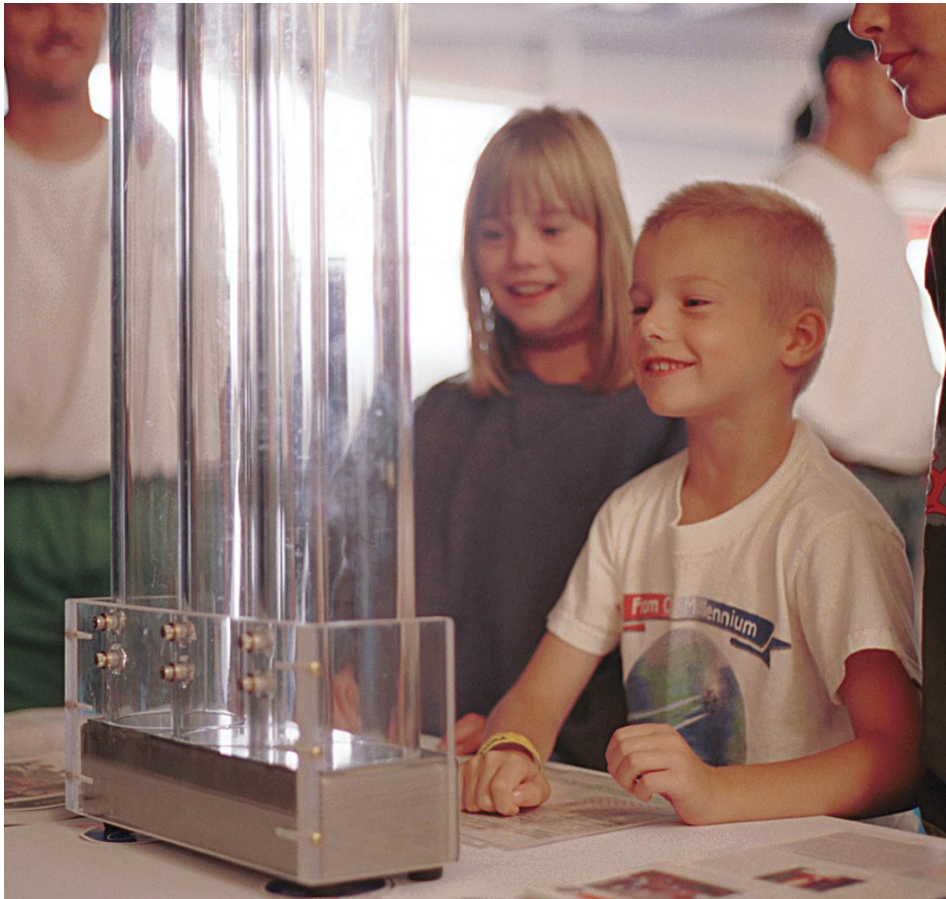
Systems engineering principles will greatly influence our organizational performance.

Our charge is to work closely with other Directorates, Centers, government agencies, industry, and academic institutions to ensure that engineering concepts and systems are interoperable and compatible with overarching program goals. Many complex systems will be developed by different organizations, and each system must interact seamlessly with the other. We will work closely with all members of the national and international space communities to coordinate requirements and jointly address cross-cutting issues.

For example, overcoming Earth's gravity to achieve orbit demands the rapid release of an enormous amount of energy under precise control. The harsh environment of space puts tight constraints on the equipment needed to perform the necessary functions. When a crew is present, a livable environment is required—air, water, food, a comfortable temperature, and waste management, as well as electrical power and control to supply and maintain these provisions. The systems providing the staples of life must have a high degree of functional reliability and must operate at a level that demands every effort to minimize risk.

Systems engineering is essential so that we can optimize the overall exploration agenda—not just any one component. The systems engineering task is complex because of the system-of-systems that must interact with one another. Another dimension of complexity results from multiple organizations that will be involved within and outside of NASA. For these reasons, integrating systems among diverse and dedicated personnel will be one of our primary responsibilities. This function will be carried out at the highest level of our organization.





The unique properties of a metallic glass, created for advanced spacecraft technology applications, are presented in a student-friendly manner (left). College students integrate science and engineering in preparation for conducting experiments in microgravity (top).

Participation by the Next Generation of Explorers

We feel privileged to develop new capabilities for exploration on behalf of all Americans. We strive to involve all Americans in our efforts by sharing publicly our challenges and our successes. Working with NASA's Education Office and the Office of Public Affairs, we will develop outreach programs, from educational curricula to museum exhibits. We will structure all of our activities to engage the minds and hearts of the next generation of explorers.

A core component of our strategy will be to develop innovative research and development partnerships with universities. We will involve the next generation of scientists and engineers in creating, designing, and crafting new approaches for our future. We will continue to enhance the

education and outreach programs previously managed by the Office of Biological and Physical Research, such as student-run experiments on the ISS. We will also involve university students in flight hardware development through the Space Partnership Development Program. In this way, we will capture student energy and innovation and begin to train new engineers and scientists to join our workforce in the future.

Transformation

Education and inspiration will be an integral part of all our programs.

—From the NASA Strategic Plan (2003)





The Sun and Earth as photographed by the crew of Columbia (STS-107).





Focused, Prioritized Requirements

“Requirement definition and subsequent control, or lack thereof [are] dominant driver[s] of cost increases, schedule delays, and increased mission risk.”

—Defense Science Board

To implement the Vision for Space Exploration and develop capabilities that are sustainable and affordable, we focus on developing capabilities within well-defined spirals. We start by defining the requirements for the capabilities and supporting technologies that are to be developed within that spiral.

Before we begin to develop a new capability, we must know why it is needed. We work closely with the organizations that will rely on the new capability to create a clear statement of objectives for the capability. Our process for formulating and prioritizing requirements gathers engineers, scientists, operators, and astronauts to craft a well-defined statement of mission objectives derived from Agency exploration goals and policy and budgetary priorities.

After documenting the essential, high-level objectives for the desired capability, we generate concepts for accomplishing the mission, including a description of how system elements will interact in an operational environment.

While an individual sailing ship may have sufficed for early Viking explorers seeking the way to a new world, today we rely on a “system of systems” to venture off the planet. Component elements (e.g., launch vehicles, space ships, habitable enclosures) can be used in a variety of ways to achieve mission objectives. How we use these elements, the “concept of operations,” is just as important as the design of the elements themselves. A viable concept of operations typically answers the following types of questions:

- In what environments are the systems expected to operate?
- How will the systems accomplish the mission objectives?
- What are the critical system parameters to accomplish missions?
- How effective or efficient must the systems be when performing missions?
- How long will the systems be in use?

These concepts of operations are distilled from a wealth of space exploration studies conducted over the past 15–20 years. We analyze lessons learned from NASA’s wealth of space flight experience, including recommendations by the President’s Commission on Implementing the Vision for Space Exploration, the Columbia Accident Investigation Board, and cumulative experience gained from the Apollo era and from operating the ISS and Space Shuttle. We involve technologists, engineers, and astronauts so that research and operational experience are considered simultaneously.

Requirements: The First Step in Exploring

Like the fictional Admiral James T. Kirk of the *Starship Enterprise*, all explorers aim “to boldly go where no one has gone before.” Every explorer initially imagines a journey, but to actually explore there must be a real vessel. Depending on the desire for capacity or speed or even luxury along the route, a different selection may result. Like the adventurers of old, NASA must determine what is important and, in so doing, establish a set of “requirements” for exploration missions. Thus, requirements formulation is the first step in a bold journey of exploration.



We recognize that there is a wealth of knowledge and talent outside of NASA. Accordingly, we complement internal NASA analyses with input from outside sources. Through Broad Agency Announcements and other contracting vehicles, we sponsor and evaluate innovative approaches from industry and academic institutions.

By evaluating and comparing different operational concepts, we identify required performance parameters for the new capability that will meet NASA mission objectives and be cost-effective. Defined along with these performance parameters are the interfaces to existing or planned systems, and the logistical and operational support characteristics of these systems. A high degree of coordination among these critical activities is necessary to derive feasible architectures, infrastructures, and vehicle design concepts within established schedule and budget constraints.

Our process for formulating and prioritizing requirements is targeted to enable sustainable and affordable exploration. An overriding goal in the definition of the requirements set for future exploration systems is to maximize value while minimizing cost. This will be accomplished by:

- Iterative analyses of cost, risk, and performance, based on realistic timelines and estimates of cost.
- Scheduling the incorporation of mature technologies to improve system effectiveness and reduce cost.
- Planning for uncertainties by establishing priorities, options, adequate margins of safety, and “off-ramps.”

The process for formulating and prioritizing requirements will rely on the use of advanced modeling and simulation tools. Before building any hardware, we will simulate vehicle element concepts and their interactions within a range of anticipated operational environments. Through modeling and simulation, we will be able to optimize design criteria and define parameters for the new capabilities. Our Capability Development Programs will then formulate acquisition plans to develop new capabilities based on specified requirements.

Our modeling and simulation analysis will also identify gaps in desired performance. We will rely on the maturation of key technologies to close the identified gaps over time. In close coord-

Formulating New Requirements

Our Requirements Division is now working with technologists, engineers, scientists and operators to develop exploration requirements for:

- A series of robotic missions to the Moon to prepare for and support future human exploration activities
- A new crew exploration vehicle to provide crew transportation for missions beyond low Earth orbit
- A nuclear electric propulsion capability (developed by “Project Prometheus”) that will enable NASA to explore Jupiter’s icy moons and provide extended power for human expeditions to the Moon, Mars and beyond.

Within this construct, the Science Directorate will provide science requirements for the robotic missions, which will be incorporated within the overall exploration mission requirements set. Once the exploration requirements are finalized, development efforts will begin. Our Directorate is responsible for developing the crew exploration vehicle and the nuclear electric propulsion capability. The Science Directorate, based on the exploration requirements that we establish, is responsible for developing the robotic missions to the Moon.



dination between our requirements team and discipline technologists, our Research and Technology Development programs will formulate technology investment plans targeted to reduce risks and cost and enhance the performance of new capabilities. In this way our requirements process will define parameters for new capabilities and identify objectives for technology development.

Once finalized, sets of requirements are documented formally and approved at the highest level of our Directorate and the Agency. In order to maintain the stability of the resulting requirements set, once requirements are approved they will become firm. Approved requirements can only be modified by obtaining written consent from the highest level in the Agency. Otherwise requirements will evolve incrementally with time and costs will grow.

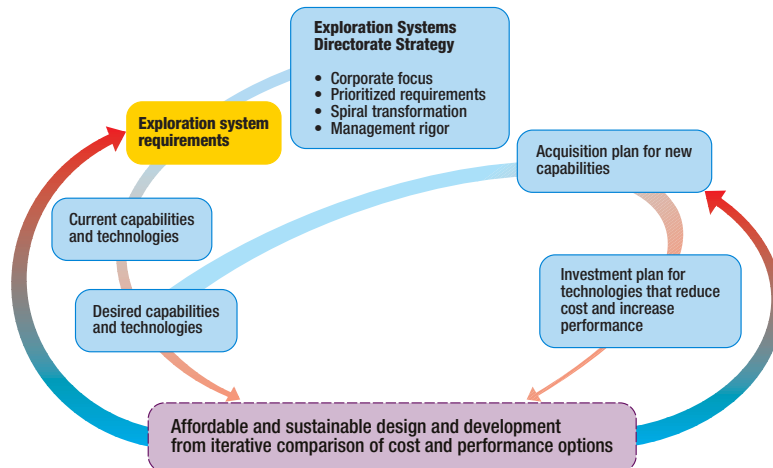
This does not mean that our in-space architecture will be inflexible. For each requirement that we establish, we will specify objectives and associated thresholds that allow for flexibility, where practical, for implementation. In addition, within each spiral, discrete requirement sets will be defined over blocks of time in a manner that anticipates the incorporation of technologies as they mature and become available for reliable in-space use. In this way, cost growth caused by requirements “creep” is effectively curtailed by accommodating, yet controlling, the incorporation of technology enhancements within the development process.

Safety: A NASA Core Value

NASA's mission success starts with safety. We are committed to protecting the safety and health of the general public, pilots and astronauts, the NASA workforce, and our high-value assets on and off the ground.

—From the NASA Strategic Plan (2003)

Requirements Derived from Iterative Analysis



These activities are not undertaken in isolation. Independent assessments and rigorous reviews ensure that cost, schedule, and performance risks are properly assessed and managed throughout the requirements formulation effort. With a particular focus on safety and mission success, these reviews will analyze technical and operational approaches, ensure that risks and risk management approaches are carefully evaluated and implemented, and identify means for verifying and validating requirements.

By utilizing all these techniques, the requirements process will formulate system architectures and vehicle designs that are optimized for success. The resulting capabilities will enable sustained exploration in a manner that minimizes risk and is effective and affordable.





Spiral galaxy NGC 1232 in the constellation Eridanus.





Spiral Transformation

NASA's exploration agenda is, by its very nature, flexible in that it depends on scientific discovery and technology maturation.

No one knows for sure what the future will bring. We cannot predict specific groundbreaking technological or scientific developments. What we are sure of is that new discoveries will occur and that they will foster exploration beyond the current space frontier.

A key challenge for the Directorate is to develop new capabilities in a manner that is pragmatic—so that new capabilities can be developed and used to advance exploration in the near term—while also being flexible, in order to incorporate new technologies and respond with agility to scientific discoveries.

To meet this challenge, the Directorate will develop exploration capabilities in stages, or “spirals.” Each spiral will usher in a set of major new capabilities in support of the Vision for Space Exploration. Spirals will be structured based on specific requirements, well-defined goals and endpoints, then-current technologies, manageable risks, an executable budget, and knowledge gained from prior in-space activities.

The Directorate's acquisition strategy will encourage the use of open-systems architectures that facilitate upgrades and augmentation, and enable interoperability between systems. Critical components developed within each spiral will be modular in order to allow for substitutions as technologies mature. This will allow for the infusion of new technologies whenever they are available, while avoiding costly redesign. For example, modular components can be substituted at minimum cost as new technology matures or obsolescence occurs. This acquisition approach will also allow for a testing and integration schedule that is flexible and efficient.

Initiation of each new spiral will require approval at the highest Agency level. This approach will allow NASA to respond carefully and creatively to new opportunities while avoiding costly redesign.

Future spirals will incorporate technologies that are then ready for in-space applications. New technologies will be considered for incorporation into the acquisition strategy for a given spiral based on a robust risk model. This risk model will ensure that new technologies are incorporated within new capabilities only after extensive analysis of potential benefits, costs, and associated risks.



A key aspect of spiral transformation will be to develop new technologies that improve performance and lower cost over time. This is crucial because current levels of technology will not allow us to achieve the Nation's goals for future exploration. Accordingly, a major portion of the Directorate's resources will be allocated to technology development. In addition, because new technologies arise from basic research, we will maintain a level of fundamental research focused on long-term applications.

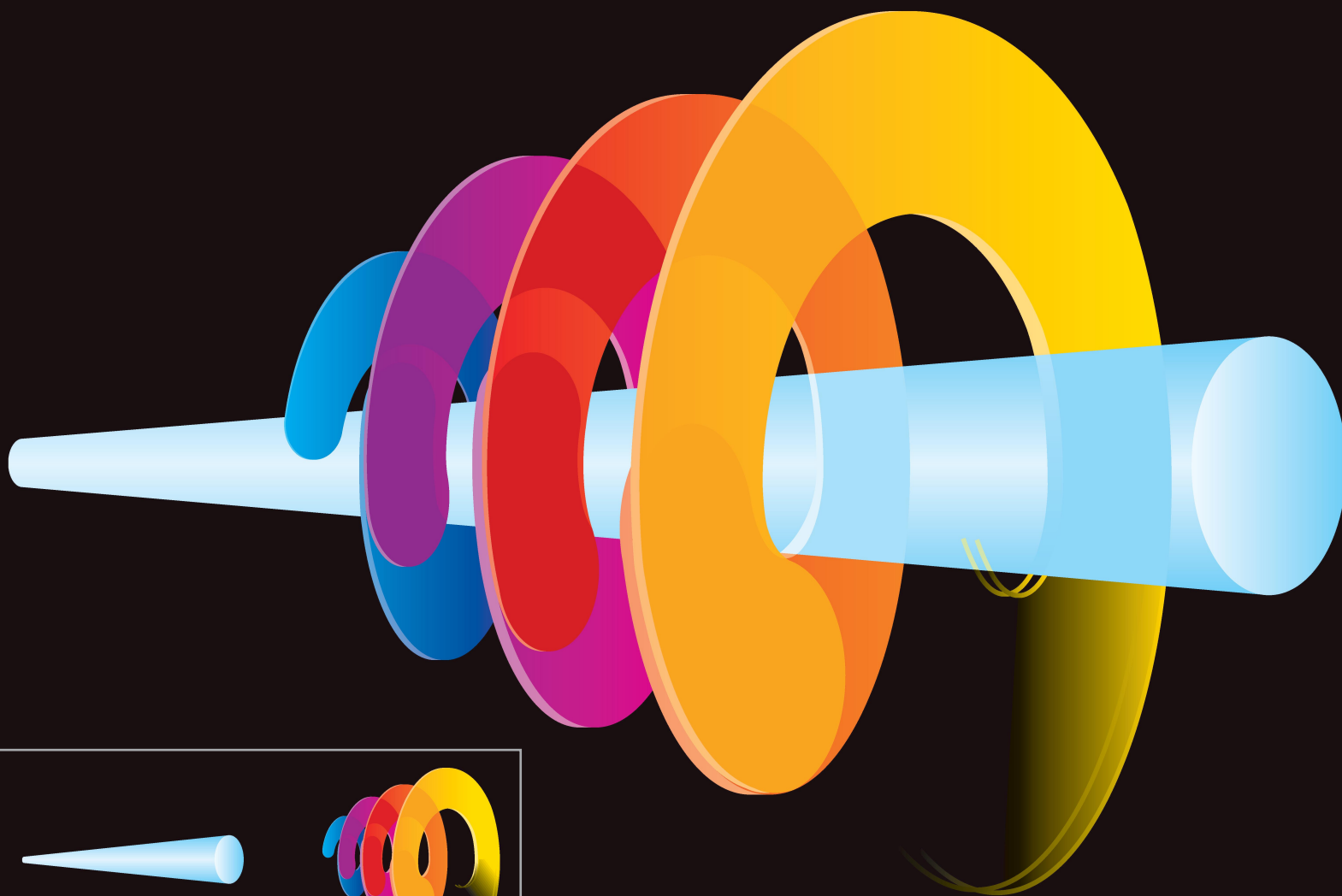
As each spiral transformation proceeds, the Directorate will seek to mature new technologies for later spirals and demonstrate that they can be effectively applied in the space environment. To do so, the Directorate will focus on advancing key capabilities such as power generation, propulsion, robotic in-space assembly, space resources utilization, and life support for more distant, more capable and longer duration missions. The Directorate's technology investment portfolio will focus on opportunities for infusion of technologies in future spirals. A rigorous strategy-to-task model will be used to analyze technology gaps, focus technology development efforts, and incorporate validated technologies into evolving exploration systems.

In the first spiral transformation, the Directorate will develop a demonstration test prototype in 2008, an unmanned Crew Exploration Vehicle in 2011, and a first crewed flight of the vehicle in 2014. We will also develop the requirements, and coordinate with the Science Directorate to initiate a series of robotic missions to the Moon that will be building blocks for future human exploration. These robotic precursor missions will begin with an orbital reconnaissance of the Moon no later than 2008. In addition, our Directorate will develop new capabilities necessary to realize specific science objectives. This may include a new robotic capability to repair, service, and eventually de-orbit the Hubble Space Telescope.

In the second spiral, the Directorate will develop the systems required to support initial human and human/robotic missions on the lunar surface. These missions will aim to reduce the risks associated with future human exploration to the Moon, Mars and beyond. Specific requirements for and authorization to proceed with Spiral 2 will be based on results obtained during Spiral 1 development. Requirements and capabilities desired for Spiral 2 will also be based on the outcome of a robust technologies maturation program, as well as the evolution of NASA's exploration and science goals.

Subsequent spiral transformations will evolve in a similar manner based on results obtained during previous spirals.





New Technologies



New Capabilities





Flight controllers oversee ISS/Soyuz docking operations.





Management Rigor

We will be disciplined managers.

Our aim is to maximize the value we provide to our customers, and ultimately the Nation.

The President's Management Agenda

We will use the President's Management Agenda to stimulate excellence in all of our activities. NASA mission support offices are developing expertise, best practice manuals, and roadmaps for all aspects of management. An Agencywide Strategic Human Capital Plan has already been issued; other Agencywide management plans are under development, including a Real Property Strategic Plan.

Included in the President's Management Agenda is the Freedom to Manage initiative. We will

Implementing Strategies

All NASA activities are based on a foundation of sound planning and management practices derived from the President's Management Agenda. NASA's implementing strategies are similar in intent to management strategies of all well-run organizations.

The NASA Implementing Strategies are as follows:

- Achieve management and institutional excellence comparable to NASA's technical excellence
- Demonstrate NASA leadership in the use of information technologies
- Enhance NASA's core engineering, management, and scientific capabilities and processes to ensure safety and mission success, increase performance, and reduce cost
- Ensure that all NASA work environments, on Earth and in space, are safe, healthy, environmentally sound, and secure
- Manage risk and cost to ensure success and provide the greatest value to the American public

—From the NASA Strategic Plan (2003)

"Making Mars a reality would require turning the space agency into a powerhouse of discipline and management . . . the likes of which haven't been seen since the '60s."

—Dr. Howard McCurdy, American University

implement flexible procedures that promote creativity and encourage open communication. Our aim is to create an innovative, inclusive, and flexible organization.

Fiscal Management

Key to fiscal management success are the business professionals who are integrated with their colleagues in all other units. The business processes implemented by the Directorate will correlate program and budget execution. Our entire Directorate will use unified fiscal systems and will operate on a full-cost accounting basis.

The Directorate's fiscal management philosophy will enable NASA to acquire needed services from the most capable sources, as required by the President's Management Agenda. Therefore, industry, universities, NASA Field Centers, and international organizations will all be able to contribute based on: (1) existing capabilities and the ability to expand those capabilities; (2) innovative solutions that meet the highest systems engineering and business standards, and (3) a demonstrated capability to implement and execute funded projects.

Freedom To Manage

Excessive control and approval mechanisms afflict bureaucratic processes . . . As the barriers to more efficient management are removed, we will expect higher performance. With Freedom To Manage will come clear expectations of improved performance and accountability.

—From the President's Management Agenda



We will operate within budget commitments. On an ongoing basis we will analyze the entire portfolio of programs to evaluate options among and within Exploration System programs, and to determine priorities based on current budget profiles. Our regular reviews will focus on demonstrable achievement on near and long-term objectives. In this way, as projects are completed on time and within budget, additional resources will be made available for additional spiral development.

Acquisition Strategy

Based on specified objectives and requirements, the Directorate will formulate an acquisition plan to develop new capabilities and invest in the maturation of essential technologies. On an ongoing and iterative basis, as new capabilities and technologies are developing, we will compare cost and performance options, trends, and results. We will use those costs and performance evaluations to refine our acquisition strategy. To conduct this iterative analysis, our business professionals will team with acquisition and technology experts from our Capability Development and our Research and Technology Development programs.

The Directorate will regularly conduct trade studies to understand the business environment and refine structures and incentives that will encourage excellence, collaboration, and innovation. The acquisition structure that we create will allow us to best evaluate substantive achievements while also fostering networks of innovation.



We will encourage teaming arrangements from organizations outside and within NASA, and will encourage competitors to propose different paths for achieving success. For each spiral and each technology maturation project, the Directorate will use an inclusive process that winnows the field of competing technologies and systems, at multiple milestones to those best suited for our applications.

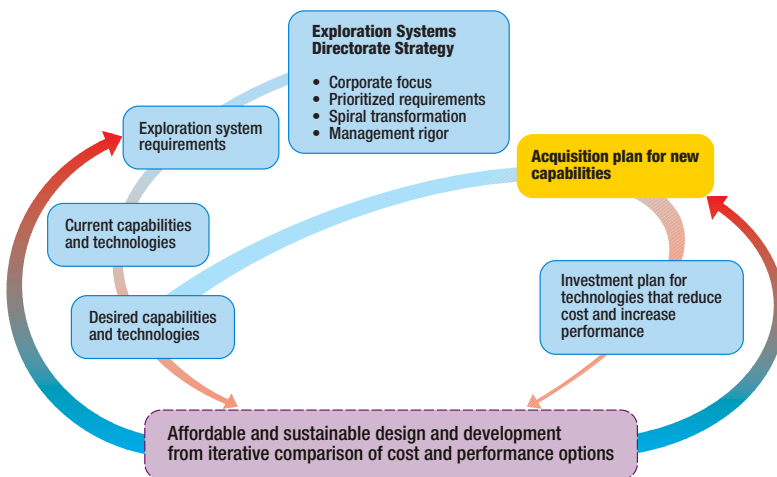
For example: the Directorate will request ideas from a wide audience and all competent sources. Through Broad Agency Announcements—a competitive process for engaging industry, universities, and NASA Centers—the Directorate will fund several concept definitions (including trade studies and demonstrations as appropriate) of those systems that are essential for success or require the longest development time. Through further competition, some of these projects will be allocated additional funding that will lead to one or more in-space technology demonstrations. Finally, at the appropriate time the Directorate will select the organization(s) responsible for final development, integration, test deployment, and support.

Rigorous Program Management and Independent Validation

The Directorate's management philosophy also requires that a program or project will receive authority to proceed to the next milestone only if:

- Entrance/exit criteria, including performance, cost and schedule targets have been met
- Risk-mitigation actions have been implemented

Acquisition Plan Derived from Iterative Analysis



- The next milestone is executable based on performance, risk, schedule, and budget criteria

Well-qualified as well as quantified metrics are necessary so that we can evaluate progress and difficulties. Performance, cost, and schedule are critical measures of success. Nonetheless, we recognize that sometimes constraints on cost and schedule can adversely affect system reliability, performance, and safety. Therefore, rigorous reviews will be conducted at each milestone to evaluate the interrelationship between defined criteria. Earned value reporting and recurring program management reviews will be used to assess reliability and safety as well as cost and schedule.

As recommended by the Columbia Accident Investigation Board, the Directorate will use independent experts to validate performance, program direction and requirements, review cost estimates, and analyze risk management plans. These independent reviews will be conducted rigorously and iteratively to ensure the highest levels of safety, reliability, and performance.



Human Resources

Our management processes will empower a proactive management team. One of the goals of the Directorate management team will be to nurture change, including cultural change, through personnel training and development. Meeting this goal will help NASA realign, nurture, and enhance core capabilities at NASA Centers, while creating an adaptive, innovative workforce. We will work with NASA's Office of Human

Resources to identify the skills we need. We will identify the competencies we must retain and those that industry, academic institutions, and others can supply. We also will develop the skills of our existing workforce and use every resource to attract new talent in essential areas.

Communications and Information Technology

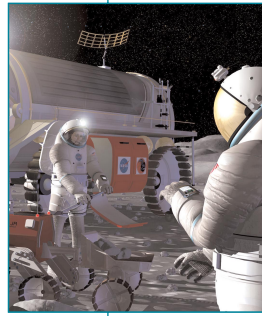
Also essential to good management practices are communications and the technologies to efficiently support communications. The Directorate will create, and actively manage Internet-based sites with updated, accurate information for both project management and public access. Additionally, we will foster openness, consistency, and clarity in communication through Agencywide presentations, industry days, and workshops.

The Directorate will invest in advanced simulation tools to facilitate design, development and testing. Our information technology management strategy will enable our Directorate to develop interoperable information systems across our programs, and make judicious decisions about investments in advanced information technology resources.

Innovation and Participation

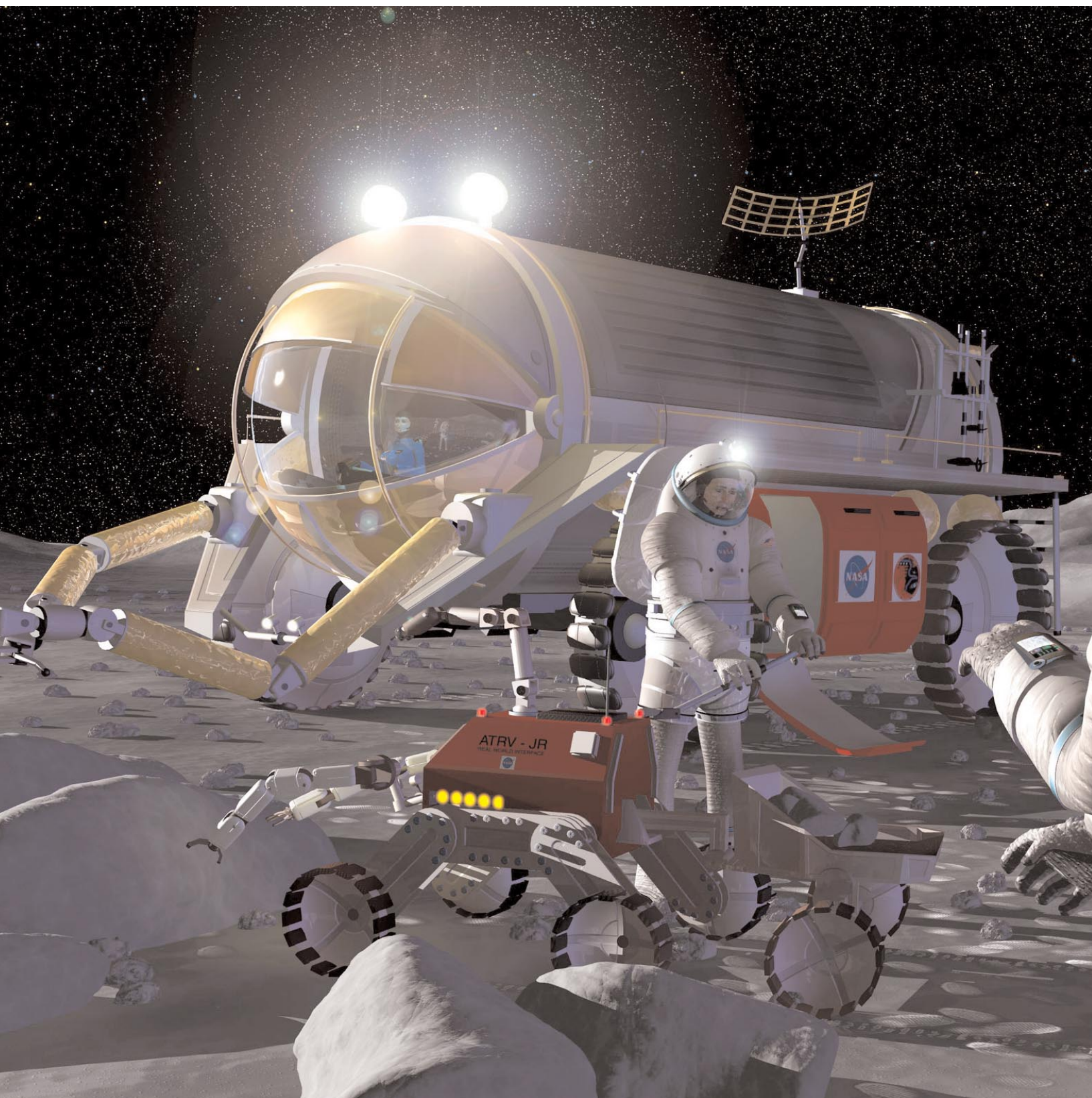
Innovation is critical. We recognize that we do not always have the best ideas, but we need them. Our programs and processes will be open for contributions from all sources, outside and within NASA. We will also create structures that encourage participation and innovation from diverse organizations. Examples are the Small Business Innovation Research Program that focuses on innovation from small businesses, and the Centennial Challenges Program that will spark innovation by offering prizes for breakthrough success in essential areas. In all of our activities, we will invite substantive participation by commercial and international organizations, and we will be receptive to considering novel arrangements that advance mutual interests.





3

Achieving Directorate Objectives



Future space
exploration mission
(artist's concept).

3 Achieving Directorate Objectives

“Every day you may make progress. Every step may be fruitful. Yet there will stretch out before you an ever-lengthening, ever-ascending, ever-improving path. You know you will never get to the end of the journey. But this, so far from discouraging, only adds to the joy and glory of the climb.”

—Winston Churchill

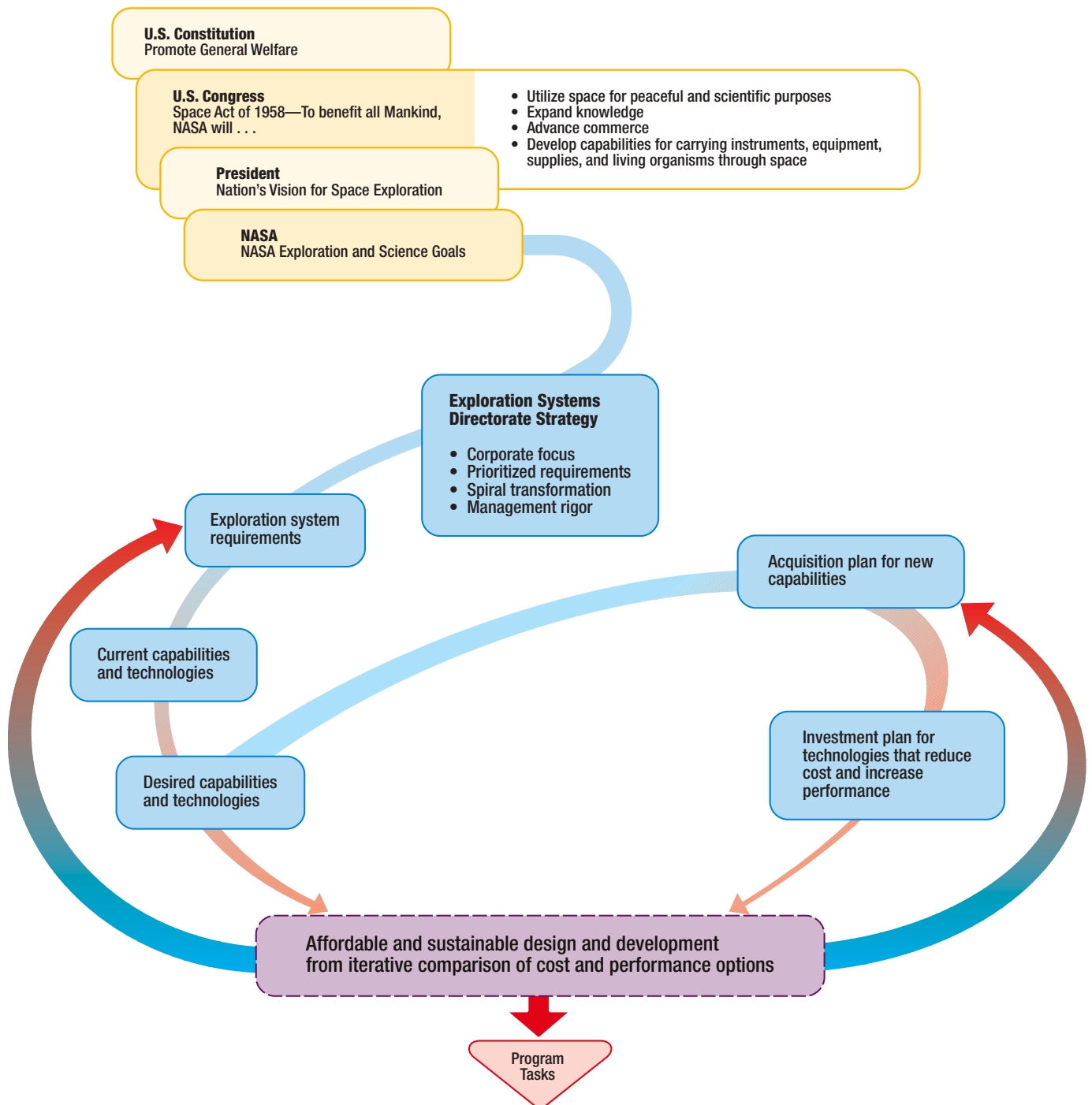
The Exploration Systems Mission Directorate programs are organized within two categories, which are:

Capability Development

Research and Technology Development

This chapter of our Strategy outlines the strategy-to-task process through which we define and prioritize program tasks. This chapter also describes our Capability Development and Research and Technology Development programs in detail, along with an explanation of how the programs will address our four areas of strategic emphasis: corporate focus, requirements, spiral transformation, and management rigor.





Strategy to Task Process

Our Strategy is derived from national space policy. The Constitution of the United States directs Congress to “promote the general welfare.” Based on the Constitution, in 1958 Congress passed legislation creating NASA. This legislation is often referred to as the Space Act. Under the Space Act, NASA is charged to:

- Utilize space for peaceful and scientific purposes
- Expand knowledge
- Advance commerce
- Develop capabilities for carrying instruments, equipment, supplies, and living organisms through space

Based on the authorities contained in the Space Act, the President in January 2004 directed NASA to focus its activities in space in order to create a robust space exploration program. This is the Vision for Space Exploration. NASA’s space exploration goals are derived from this Vision. In turn, our Directorate Strategy is targeted toward developing new capabilities and supporting research and technologies that will enable NASA to implement its exploration and science goals.

Just as the Exploration Systems Directorate Strategy is derived from national space policy, our programs derive their tasks from our strategy.

Through a corporate focus on the Vision for Space Exploration, we work in tandem with experts in other NASA Directorates to define focused, prioritized requirements for new capabilities and supporting technologies.

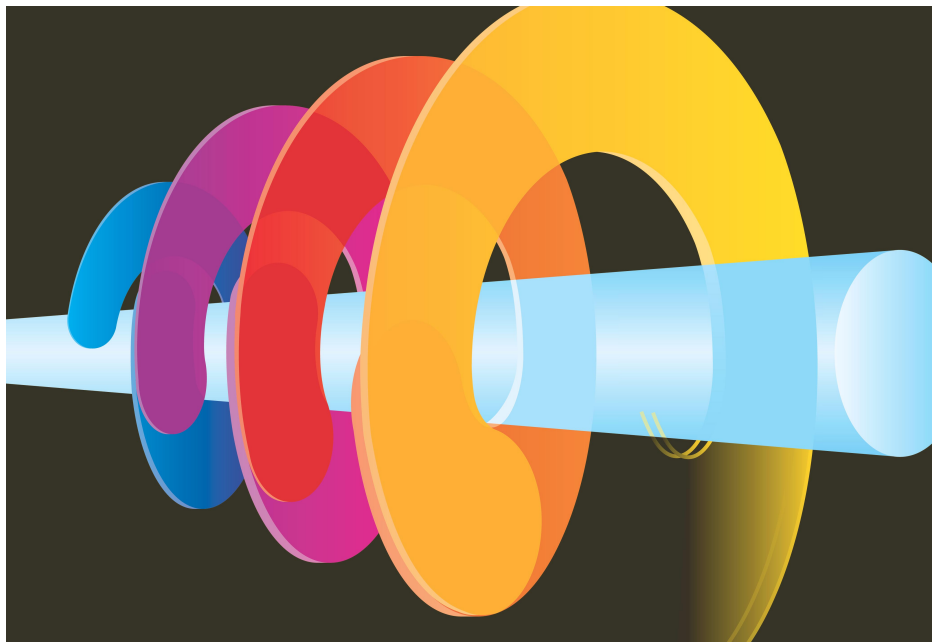
Based on specified requirements, a constellation of new capabilities and supporting technologies will be developed within well-defined spirals. Future spirals will evolve based on the maturation of new technologies.

Our specific program tasks derive from management rigor—a disciplined approach to management that includes an acquisition and investment plan targeted toward building new capabilities and engaging in essential research and development.

The process of flowing from our strategy to program tasks is iterative. Our strategy for ensuring affordable and sustainable design and development requires extensive modeling and simulation of concepts and their interactions within a range of anticipated operational environments. Cost, performance, and risk data are evaluated iteratively to determine the optimal:

- Requirements set and priorities
- Design for desired capabilities
- Acquisition plan for new capabilities
- Investment plan for research and technology development

Like our overall efforts, this strategy-to-task process is spiral in nature in that, through repeated analysis of costs and performance options, trends and results—including progress in developing specific capabilities and progress in maturing essential technologies—we spiral towards the deployment of new, transformational capabilities in a manner that is safe, effective, and affordable.



*“We leave as we came, and God willing, as we shall return,
with peace and hope for all mankind.”*

— Eugene Cernan, Commander of
the last Apollo mission



Capability Development

“When we mean to build, we first survey the plot, then draw the model; and when we see the figure of the house, then we must rate the cost of the erection: which if we find outweighs ability, what do we then but draw anew the model in fewer offices, or at last desist to build at all?”

—William Shakespeare, from *King Henry IV, Part II*

We develop new capabilities within well-defined spirals.

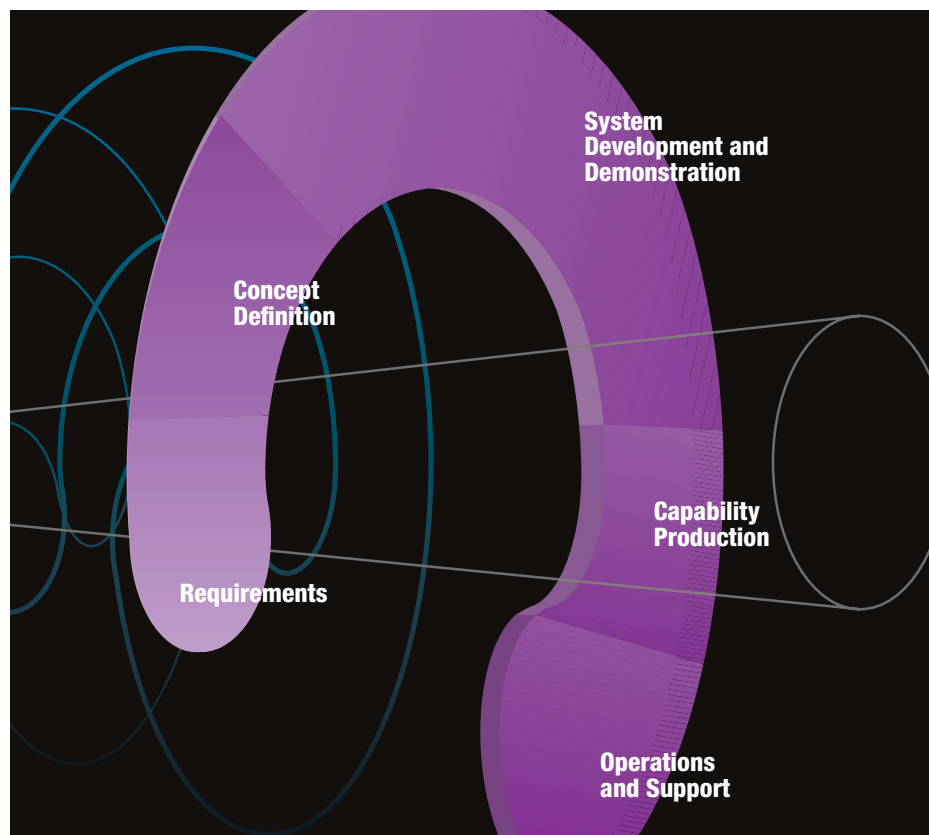
Each spiral begins with the formulation of objectives and requirements, based on iterative strategy-to-task analyses, and the availability of then current technologies.

Once requirements are defined, we seek ideas concerning any aspect of capability development from all interested organizations and individuals, both within and outside NASA. Through Broad Agency Announcements, we consider proposed concepts for developing the desired capability. Selected concepts are then refined through a competitive process that includes rigorous evaluations of cost and schedule estimates.

After deciding on the final development concept, we engage in system development and demonstration. This extended stage of development includes testing, integration, independent design and readiness reviews, and risk reduction through the infusion of technologies that were successfully matured.

Each development stage relies upon ongoing strategy-to-task analyses and independent reviews to assess progress based on performance, schedule, cost, technologies, risks and risk mitigations plans, and other entrance/exit criteria. In this way, at every stage within a development spiral, we will determine whether the development program should continue.

When system development is completed successfully, the new capabilities will be produced and deployed and then transferred to the Flight Operations or Science Directorates for in-space operations and support.



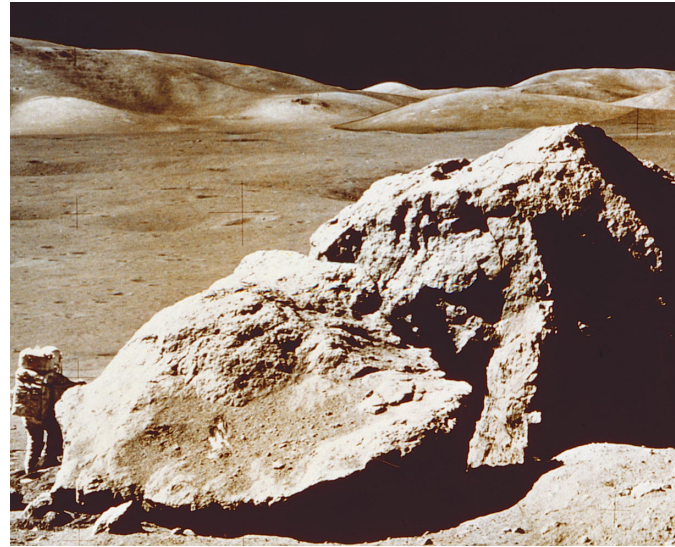
A view of Earth as seen from the Moon by Apollo 11 astronauts (opposite page).



Our Capability Development programs will build on NASA's rich legacy of operational human and robotic space exploration as evidenced by Mercury, Gemini, and Apollo, the Shuttle and the International Space Station, and Mars robotic exploration.

The Directorate's development strategy will focus first on creating capabilities for sustained and affordable human and robotic exploration of the Moon, in preparation for more challenging missions to Mars and other destinations in deep space. A critical objective, as articulated in the Vision for Space Exploration, is to develop the system-of-systems that are necessary for a first extended human expedition to the lunar surface to begin by no later than 2020, and as early as 2015.

The new capabilities developed for use in Earth-Moon space, lunar orbit, and on the lunar surface will provide the Nation with a flexible and robust architecture that can be used to meet varying objectives at diverse destinations. This system-of-systems will encompass robotic orbiters and rovers, crew transportation, cargo transportation, surface exploration, in-space and ground support, and a wide range of technology and systems demonstrations. Planning for these transformational new capabilities is just beginning. Future decisions will be based on well-



Astronaut Harrison Schmitt examines a geological formation on the Moon (top). The Mars Opportunity Rover gathers data from a geological formation on Mars (top right). A key challenge for the Directorate is to develop capabilities that enable humans and robots to work together more effectively and thereby enhance the potential for scientific analysis and discovery.

established requirements, budgetary priorities, trade studies and other analyses of costs, benefits, and risks, as well as progress in diverse areas of research and technology development.



Corporate Focus

The Directorate's Capability Development programs will draw on talent from many organizations outside NASA in order to implement the Vision for Space Exploration. This includes industry, universities, other government agencies, and international participants. To this end, we regularly hold public sessions to explain progress and plans. We also rely on the Internet and other mechanisms to facilitate information exchange between the Capability Development programs and participating outside organizations.

Efforts within NASA that support the Vision for Space Exploration are not limited to our Directorate; they span the entire Agency. Integration across the NASA Directorates is critical to the successful implementation of the Vision, and our Capability Development programs focus on effective integration with other NASA Directorates. For example, launch system and space communications options are developed in coordination with the Space Operations Directorate, which provides space flight services for NASA activities in space.

Design and mission options are coordinated with the Science Directorate, which will develop the robotic lunar missions that serve as a precursor for human exploration. Because of the tight connection between the lunar and human missions, an Exploration Systems Review Board has been created under the leadership of the Directorate's Deputy Associate Administrator. This Board will coordinate the capability development efforts being undertaken by the Exploration System and Science Directorates. Executives from all NASA Directorates participate on the Board to allocate requirements, resolve differences, and create an intra-Agency culture that promotes cooperation and synergy.





Through close cooperation among the Exploration Systems, Science and Space Operations Directorates, the Agency will launch a series of robotic missions to the Moon in order to characterize surface operating environments that will support future operations. Scheduled for launch in 2008, a Lunar Reconnaissance Orbiter will gather data for high-resolution maps of the Moon that better define its topography and resources. This will enable selection of sites for later robotic landers as well as for eventual human missions. Orbiter data will also help to determine the availability of materials on the

Moon that may be useful for human exploration, and identify opportunities for scientific investigation of geological features that hold evidence of early Earth's chemical composition and accretion processes. Subsequent robotic missions to the lunar surface may validate key technologies for later human missions and may conduct initial geological investigations in preparation for more ambitious science that will be pursued by subsequent human and robotic lunar missions.

By the middle of the next decade, robotic operations at the Moon should establish basic communications and navigation infrastructure for extended human and human/robotic operations. Navigation beacons and telecommunications relays placed robotically will create a high-bandwidth communications network at the Moon and prepare for crewed missions that require precise, repeatable and affordable landing of architectural elements.

Successfully implementing a timely campaign of early lunar robotic missions will reduce the risks and life-cycle costs of future human operations at the Moon, build valuable mission operations experience, and provide insight into the preparations required for extended human travel to Mars and other destinations in the Solar System. As early robotic missions prepare the way for

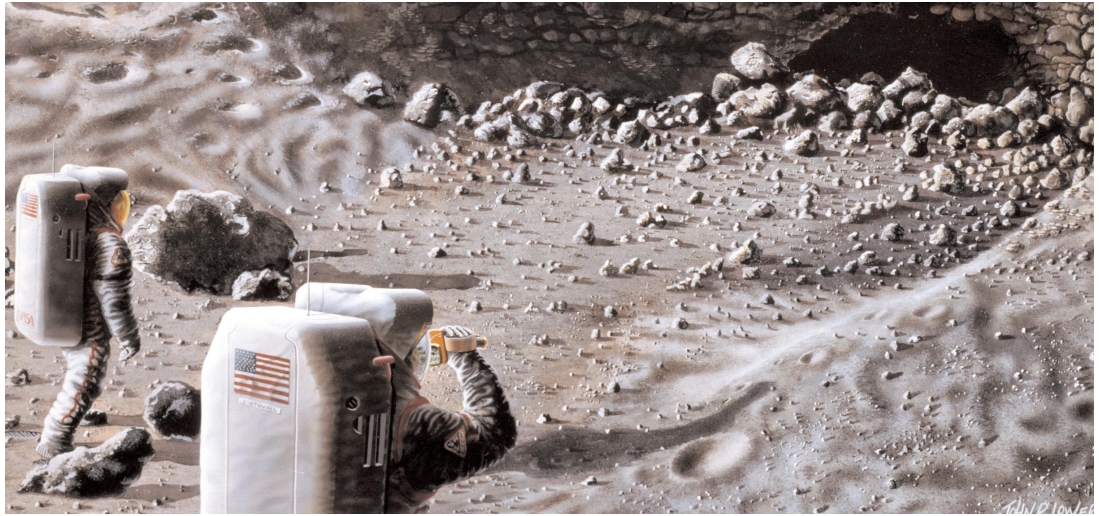
Corporate Focus *(continued)*

In addition to coordinating integration efforts with other NASA Directorates, our Deputy Associate Administrator also coordinates contributions from all NASA Centers. Weekly meetings are held between our Directorate and core capability experts at each NASA Center to encourage open dialogue and forward progress.

Our Capability Development programs also work closely with other divisions within our Directorate. For example, all capability development efforts flow from requirements formulated by the Requirements Division. In addition, each new capability will benefit from matured technologies developed by the Directorate's Research and Technology Development programs. Similarly, essential research conducted on the International Space Station will impact the design and development of capabilities for human exploration. Our Capability Development programs also coordinate closely with the Directorate's Business Division to facilitate the issuance of BAAs and other competitive announcements. In this way we ensure that key decisions are vetted by individuals within our Directorate that have technology development and acquisition experience. We also routinely seek advice from scientists and astronauts in other parts of the Agency who will rely on the capabilities that we are developing.

We compliment our risk reduction efforts by relying on advice and guidance from NASA's Office of Safety and Mission Assurance and the NASA Engineering and Safety Center based at Langley Research Center. These organizations enhance the safety and mission success of all NASA activities through the development and oversight of Agencywide procedures. This process involves reviewing our projects on an independent basis, creating and implementing cutting-edge test and evaluation techniques, and checking our work against established standards.





Crew members surveying to find a suitable location for their lunar base (artist's concept).

sustained human and robotic lunar exploration, a development team comprising industry, government, and others will design, develop, and launch the first of a new generation of systems that will enable space operations by U.S. astronauts on the Moon and beyond. These development projects will first focus on the development of a CEV, a human-rated launch capability, and other critical supporting systems.

Our Directorate will ensure that initial investments lead to a CEV system that supports multiple applications with low recurring operations and life-cycle costs. Critical to this effort will be the development of a human-rated launch system for the CEV. Since recurring infrastructure

costs have a substantial effect on life-cycle costs, selection of a CEV launch vehicle will be influenced greatly by a launch vehicle provider's ability to minimize infrastructure and associated manpower requirements. Additionally, technology maturation activities by our Research and Technology Development programs will further improve reliability, reduce life-cycle costs, and increase the anticipated effectiveness of the suite of future exploration systems.

As an anchor for NASA's system-of-systems architecture intended to enable exploration involving multiple destinations and diverse objectives, the CEV design will be extendable so that it can perform multiple functions. The overall crew trans-

Focused, Prioritized Requirements:

Requirements for the CEV and its launch system are being developed by the Directorate's Requirements Division. Representatives from our Capability Development programs participate with the Requirements Division to assure that requirements are verifiable, affordable, and achievable, and that unnecessary risk is not built into the development programs. A work breakdown structure used by both organizations frames the requirements flow from concept to implementation. Mission operations concepts are being developed early in the requirements development process to ensure that issues that may impact cost, schedule, and risk of mission success are fully considered as early in the process as possible.

Overarching requirements distilled from the Vision for Space Exploration (called "Level-0 requirements") have been developed by NASA, in coordination with the White House Office of Science and Technology Policy. These Level-0 requirements are listed in appendix 1.

From these Level-0 requirements, our Requirements Division derives "Level-1" requirements for the exploration system-of-systems, including the CEV. Level-1 requirements are coordinated with all NASA Directorates and approved by the NASA Strategic Planning Council.

Level-1 requirements and key performance parameters for the CEV are defined by carefully assessing and comparing options that vary based on anticipated performance, cost, schedule, and risk.

For each CEV requirement that we establish, we will specify objectives and thresholds that allow for flexibility, where practical, for implementation. Once



Constellation Systems: Creating System-of-Systems Capabilities for Sustained Exploration on the Moon and Beyond

Based on studies conducted by our Requirements Division, and driven by their results, the Directorate's Constellation Systems Office will develop, demonstrate, and deploy successive generations of capabilities that will enable the United States to achieve the vision of sustained human and robotic exploration on the Moon and beyond. Technology and advanced systems development and demonstration activities will be undertaken to establish critical capabilities that will be essential for all phases of lunar exploration.

The capabilities to be developed will form a system-of-systems that include:

- **Robotic Precursor Systems:** The first steps in our journey of exploration will be taken by robotic systems—orbiting, landing, and operating on the Moon as precursors to later human explorers. We are working closely with, and providing requirements to the Science Directorate, which is responsible for managing a series of robotic lunar missions that will pave the way for human exploration.
- **Crew Transportation:** The initial focus for the Constellation Systems Program will be to develop a Crew Exploration Vehicle (CEV) that will carry future astronauts from Earth to space, and from point-to-point in space. Initial high-level milestones include a CEV demonstration flight in 2008, a CEV flight without crew in 2011, and a CEV flight with crew in 2014. Along with building the CEV, we will select the appropriate human-rated launch vehicle.
- **Cargo Transportation:** The cargo we transport may include fuel and supplies, as well as transportation modules and supporting infrastructure that will be used in space or on the lunar surface. In cooperation
- with the Space Operations Directorate, trade studies are underway to evaluate launch vehicles and optimize the number of launches required to implement a given mission. Multiple components may be launched from Earth, assembled in Earth orbit or other locations, and then transported for use in lunar orbit or on the Moon.
- **Surface Systems:** The capabilities we deploy on the lunar surface will support diverse mission phases, including lunar landing, surface operations, and ascent from the lunar surface. The variety of system-of-systems needed are still being defined, but could include systems for surface mobility, robotic assistants, extravehicular activity, habitation, scientific platforms such as telescopes, and surface-based power generation.
- **In-Space Systems:** We may also enhance, in cooperation with various other Directorates, NASA's space-based infrastructure. This may include additional communication networks, service platforms for maintenance and supply, and zero gravity extravehicular capabilities like evolved space suits.
- **Ground Systems:** In cooperation with other Directorates, we will rely upon or enhance NASA's existing ground-based systems to support mission operations, preflight integration and logistics, and mission simulation and testing.
- **Humans as a Critical System:** We will create new capabilities by focusing on the human interface so that humans can live and work in space productively without suffering long-term health consequences.

portation system that will evolve from the basic CEV design will enable ascent and entry in the Earth's atmosphere, Earth orbit, transit of deep

space, and operations at the Moon, Mars, or other locations.

Focused, Prioritized Requirements: *(continued)*

defined, requirements will be rigorously controlled. As demonstrated in many past development programs, lack of requirements definition and control leads to cost growth, schedule slips, and additional technical and programmatic risk. Once approved, requirements may not be modified without obtaining the written consent of NASA's Strategic Planning Council.

As the Vision for Space Exploration matures, requirements will be developed for launch systems that will take humans to space and provide a capability to deliver cargo as well. Like the process used to develop CEV requirements, the requirements process for launch systems will involve NASA engineers, astronauts and scientists as well as industry partners. These requirements will provide the basis for identifying the additional safety measures that will have to be implemented so that a launch system and CEV, when operating together, can be used for crewed flight. Early in 2005, we expect to begin to seek input on concept approaches and designs for launching the CEV.

Selection of launch systems for heavy cargo and propellants will also be studied. New commercial launch systems may yield lower-cost options that augment the existing Evolved Expendable Launch Vehicle and Shuttle system portfolio, permitting greater architectural flexibility and cost-effectiveness. At the same time, demonstrations of on-orbit rendezvous and docking capability may open the possibility for architectures that launch in smaller packages and are assembled in orbit. This strategy also provides time for the maturation of on-orbit refueling systems, high-energy propulsion systems, modular space systems, and lunar resource utilization technologies, all of which have the potential to substantially reduce per-mission launch mass requirements.





Exploration on the lunar surface (artist's concept).

Designing the Systems that Support Sustained Lunar Exploration

The design for the systems that support sustained human and robotic exploration on the Moon and beyond will be derived from a competitive process. As outlined in our acquisition plan, industry-led teams will propose different concepts. The final design will be the end product of an extended competition that winnows ideas based on demonstrated progress.

Although we do not know how these systems will eventually be designed, we can describe factors that will influence design decisions. These factors include:

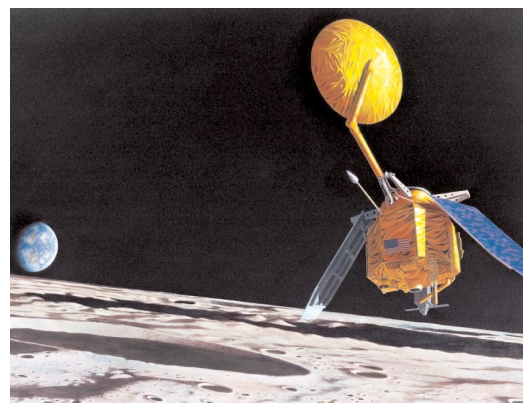
Technology Maturity: Determining what technologies are viable for incorporation into planned capability development efforts, including the 2008 CEV demonstration flights, the 2011 first flight without crew, and the 2014 first crewed flight.

Lessons Learned: Evaluating previous operational human and robotic exploration activities. This includes NASA's collective experiences from Apollo, the Shuttle, the International Space Station, and Mars robotic exploration, as well as findings and recommendations from the Columbia Accident Investigation Board.

Safety: Establishing risk limits, maintaining crew health and performance after long-duration missions, and evaluating crew escape, return, and safe haven options during all phases of operation.

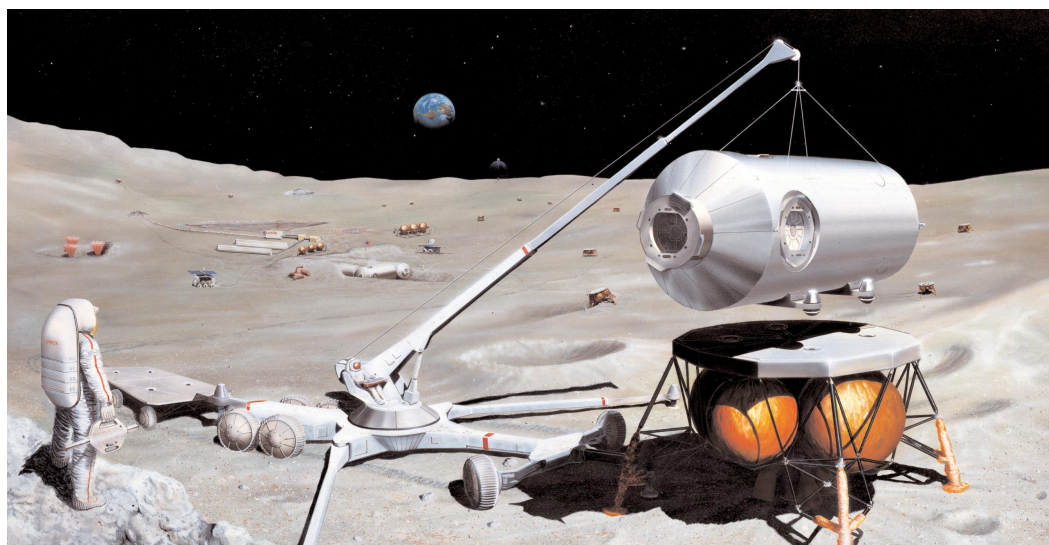
Affordability: Examining issues associated with the cost per vehicle of potential approaches, the cost per mission using these options, and the cost over many missions.

Complexity: Endeavoring to reduce technological and interface complexities in the CEV and associated systems to increase reliability and decrease cost.



An orbiter surveying the lunar surface (artist's concept).





Lunar surface crane removing a newly arrived habitation module (artist's concept).

Effectiveness: Striving to adopt system concepts that will enable repeatable, precise, affordable access to global sites on the Moon.

Crew Size: Examining how crew size affects different design and operational concepts concerning safety, health, autonomy, cost, and effectiveness.

Crew Support and Interfaces: Evaluating environmental and other life support technologies and countermeasures that enable long-duration human space travel. This includes analyzing how humans should be best augmented by machines so that crews can operate in space as effectively as possible.

Extravehicular Activity: Considering system designs that ensure safety and maximize performance for humans conducting extravehicular activity in surface and space environments.

Mission Operations Support: Considering how mission operations can evolve to support crews in long duration space flight. This includes maintaining in-flight crew proficiencies over long-duration missions, and spacecraft systems management.

Commercial and International: Providing opportunities and evaluating options for commercial and international participation.

Using the Moon as a Test Bed for Future Exploration

The Moon will be used to develop and test new exploration approaches, technologies, and systems that can be used to improve reliability and advance exploration capabilities for many future destinations.

Since the Moon is only a few days away from Earth and new missions could launch as frequently as every two weeks, the Moon offers a convenient test location far enough from home to be challenging, but not so far as to limit its usefulness as a location for development and testing.

For many new systems, core components will be developed that can be used in multiple architectures at diverse destinations. We will test these systems and components on and near the Moon to determine how they operate in harsh lunar and space environments. The Moon will also provide the opportunity to understand how crews adapt and perform in a partial-gravity environment. Before deploying essential systems to more distant destinations, we will ensure that the systems can operate without immediate assistance from Earth. This will be of particular importance for human life support systems that will be relied upon for missions to Mars and other distant locations in the Solar System.

We will also strive to enhance interactions between human explorers and robots. By working together in space, they will achieve more than either robots or astronauts can do alone. New designs for efficient and effective flight and surface operations will also be evaluated. In addition, we will analyze the use of lunar and other space resources for power generation, propulsion, and life support.

As we use the Moon as a test bed for future exploration, we will also seek to advance discovery and understanding by conducting scientific experiments on the Moon that help resolve fundamental questions about the origin and evolution of the Moon, the Earth, and the Solar System. We also may use the lunar environment as a location to learn more about meteors, asteroids, comets, and other astronomical phenomena.



Acquisition Plan for the Crew Exploration Vehicle

We will create an acquisition plan for each new capability that we develop. Our initial plan is focused on the CEV. We will develop a similar acquisition plan for all capability development efforts.

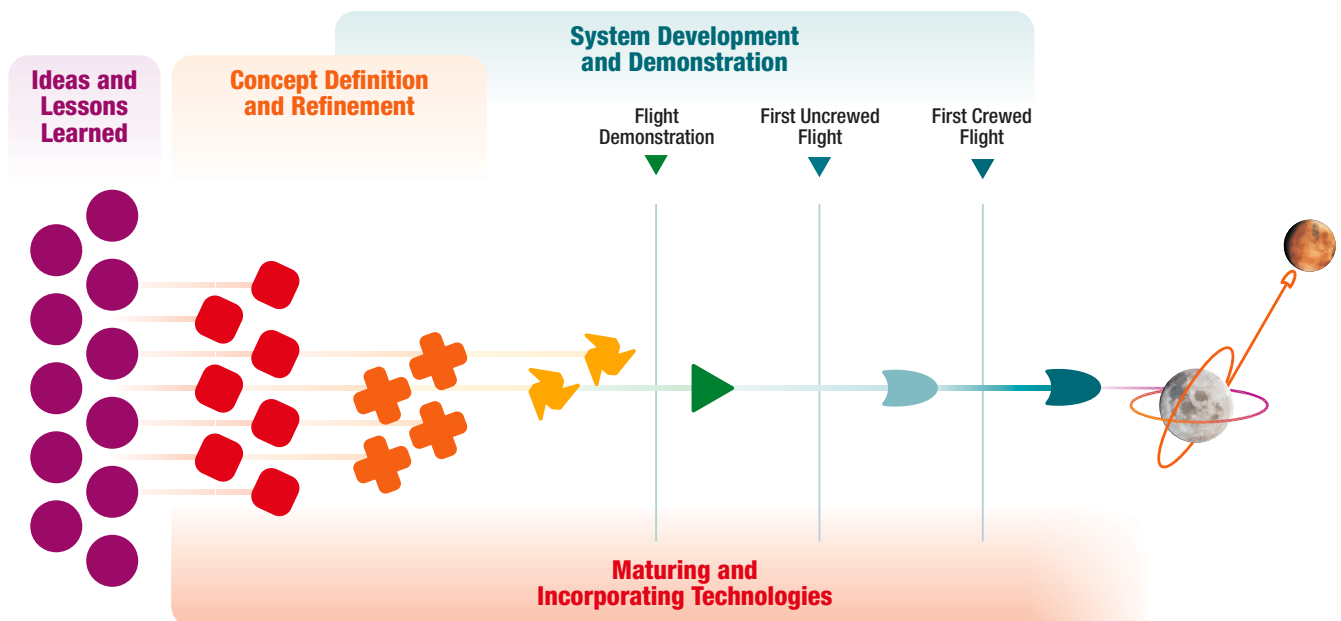
Redirecting existing NASA programs and projects is the first step toward molding an integrated acquisition approach for the CEV. To that end, NASA's Orbital Space Plane and Next Generation Launch Technology Programs collected assessments of lessons learned, applications of best practices, and insights regarding the efficacy of engineering trade studies performed under the contracts. These reports, generated by contractor and NASA teams, serve as a foundation for CEV development efforts.

Along with the experience obtained from past NASA programs, an essential component of our CEV acquisition plan is to seek ideas from a broader constituency. We issue Requests for Information (RFIs) from all sources within and outside government that address

initial challenges confronting our Capability Development programs in general, and the design and development of the CEV in particular. We seek input on a wide range of design options to accommodate variations in crew size, complexity, human-robotic interfaces, and mission operations.

As the next step in our acquisition strategy, our Directorate seeks proposals for concept development and refinement by issuing a Broad Agency Announcement (BAA). Information derived from previous NASA programs and from prior RFI input is used to scope the BAA and evaluate the BAA proposals. Awards to multiple industry teams are contemplated so that industry can refine innovative and promising concepts for CEV design with an emphasis on functionality within the lunar mission architecture, as well as risk prioritization and mitigation. Winning teams will work closely with our Requirements Division to help refine and validate requirements. International participation is encouraged through teaming or subcontractor arrangements with U.S. prime contractors.

Developing the Crew Exploration Vehicle



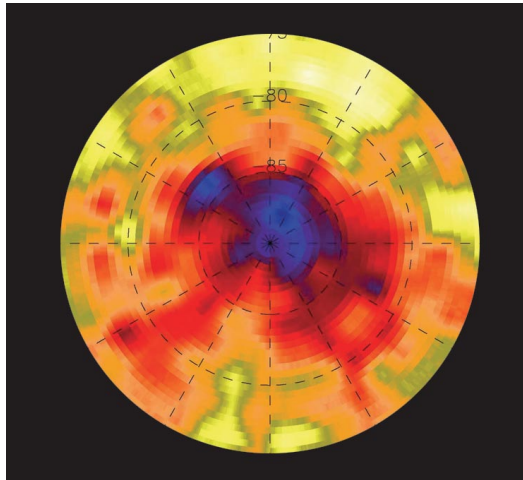
The Directorate will begin system development and demonstration on the basis of success demonstrated in BAA awards. To do so, we will issue a Request for Proposals (RFP), through which we will fund selected industry-led teams. At this acquisition stage, NASA Centers will be encouraged to participate with potential prime contractors. The industry-led teams will seek to mature their CEV concepts, demonstrate viability, and reduce integration and manufacturing risk. Information derived from the BAA and RFP processes will help us: evaluate proposed 2008 CEV flight demonstrations to determine whether they are reasonable and achievable, assess the key CEV systems and subsystems that should be validated by means of flight demonstrations, determine how the CEV should best evolve from a flight without crew in 2011 to a crewed flight in 2014, and determine the type of test program that should be employed before the first lunar landing.

Depending on the availability of funds, we expect to support several initial system development efforts from at least two competing teams. These initial system development efforts will help us evaluate progress in technology maturation and risk reduction. Our plan is to select at least two flight demonstrations that will seek to demonstrate the in-flight viability of competing concepts and the ability of contractor teams to carry out system development from conceptual design to testing. It will not be necessary to fly a completed CEV at this time. Instead, the emphasis will be on selecting a flight demonstration best able to mitigate risks associated with a particular CEV concept.

The final acquisition stage will involve the selection of one industry-led team to mature, test, and produce the CEV. This selection will focus on demonstrated success within three categories:

- Success in reducing risk through the flight demonstration
- Success in reducing risk by maturing and incorporating technologies
- Success in planning and design for future CEV flight operations

For each acquisition plan used to develop the Exploration System system-of-systems, such as the CEV, the objectives and processes will essentially be the same. For example, in each acquisition plan, we will strive, where possible, to continue competition as long as feasible. We will also use RFIs, BAAs, and RFPs to continue to define achievable requirements, determine optimum trades, and reduce or minimize risks through targeted demonstration projects.



A false color map of the Moon indicating the presence of hydrogen in blue. The south pole is at the center of the image.

A Possible Destination on the Moon: the South Pole

The south pole of the Moon (pictured above) is one of our possible destinations for extended lunar exploration. Remote sensing spacecraft in 1994 and 1998 identified polar cold traps on the lunar surface—in permanent shadow—as likely containing hydrogen, possibly as water ice. If the presence of hydrogen and other important elements is confirmed, lunar materials could be made into propellants, breathable air, and other consumables, reducing the dependence of future human missions on a logistics train extending from Earth and enabling a truly system-of-systems impact on the overall space exploration vision.

Making use of this space resource would require extensive effort. We would first have to function as "prospectors," confirming where the water is and determining its composition. Then, as "miners," we would have to excavate water-bearing "ore" from craters and then remove the water and other useful material. This will require the development of low-gravity mining and beneficiation technologies that are analogous to those on Earth, but with challenging twists, including the requirement that they operate at low gravity (1/6th g) and in extreme cold (-200° C).

By proceeding in this manner, the Moon would be used for testing and reducing the risks associated with developing space-based resources in other locations in the Solar System like Mars. Carbon dioxide in the Martian atmosphere, and water ice available near the poles, could be tapped to provide air for visiting expeditions and propellant for the return trip home. This could reduce the resources that would otherwise have to be launched from Earth in support of those future missions.



Systems Engineering: Vital for Success

When developing all new capabilities, we will rely on systems engineering principles to integrate components, subsystems, and systems.

Systems engineering involves the rigorous implementation of processes necessary to separate elements of the system-of-systems into manageable work elements and then analyze those elements so they can be effectively integrated into a complex final product that meets requirements. These processes include interface optimization, risk management, and configuration control.

One of the key elements that can greatly affect priorities is the level of acceptable technical risk in developing the systems. In order to evaluate these risks and define technology needs, systems engineering processes must, in many cases, continue functional decomposition down to the subsystem and component level in order to assess the need for new technologies. This effort must be particularly robust for those systems that will incorporate new technologies that must be matured prior to system acquisition.

Rigorous systems engineering requires ongoing surveillance over design and development activities and detailed analysis of systems, subsystems, and components to determine whether they can work together to provide the desired capabilities effectively. Along with this functional evaluation, analyses are conducted to evaluate the cost, schedule, and risk of developing and operating these systems and their constituent elements. On an iterative basis, trades between systems, subsystems, and critical components are analyzed in an integrated modeling and simulation environment so that the overall performance of the new capabilities can be evaluated.

Systems Integration

Along with selecting an industry-led team to develop and produce the CEV, we will identify the best way to ensure compatibility within the Constellation system-of-systems.

To define the appropriate organization for systems integration, we asked the National Academy of Engineering to convene a panel of eminent experts from industry, government, and universities. The National Academy's panel will:

- Review lessons-learned from government-led and industry-led integration efforts

- Evaluate whether experience in complex systems integration is sufficient or whether specific, space-based experience is required
- Evaluate the appropriate roles and relationships of industry and government
- Establish criteria for selecting a successful systems integrator

After analyzing the Academy's report, we will employ the recommended criteria to select a systems integrator.



Spiral Transformation

Capability development takes place within spirals that are concluded successfully with the delivery of needed capabilities.

The first set of capabilities will encompass the CEV and lunar robotic missions that serve as a precursor for human exploration. These capabilities are an essential core around which greater capability will be developed in future spirals—so that NASA can conduct extended human missions to the Moon, and then to Mars and beyond.

Requirements for new capabilities are established at the beginning of each spiral, followed by concept definition, systems development and demonstration, capability production, and operations and support. Affordability is achieved through iterative risk assessments and technology gap analyses.

We organize our capability development efforts within defined spirals, but we do not create capabilities ourselves. We rely on the creativity and talent of industry-led teams to propose and demonstrate innovative concepts and build new capabilities. For each spiral, we create an acquisition strategy tailored to marshal competitive processes so that we can obtain the best results for the American public.

Within each spiral, we also rely heavily on the incorporation of mature technology to increase performance and reduce costs. There are two ways in which technology can be infused within a spiral. First, technologies that are already mature and do not create developmental risks can be incorporated at the beginning of the spiral. Secondly, our capability development efforts will rely on open architectures that allow for the incorporation of new technologies as they mature. Thus, as new capabilities are developed, technologies that become mature can be incorporated within the developing capability.



New Capabilities for Science and Capability Demonstrations

Based on emerging science requirements, our Directorate may be tasked to develop capabilities that will meet specific science objectives while also enabling human and robotic exploration on the Moon and beyond.

To this end, in close cooperation with the Science Directorate, we are now obtaining and evaluating proposals to robotically maintain, repair and/or de-orbit the Hubble Space Telescope. Our evaluation process will involve rigorous analyses of cost, risk, and performance options.

Based on those technical and cost evaluations, our Directorate may be tasked to develop a robotic capability that will meet specified mission requirements for the Hubble Space Telescope. If so, we will employ the same processes used for all capability development efforts, and we will implement an acquisition plan for designing, testing and deploying this new capability in a manner that reduces the risks associated with future exploration.



Hubble Space Telescope

Spiral Transformation *(continued)*

Some revolutionary technologies will require many years to mature; therefore their application will transform future spirals.

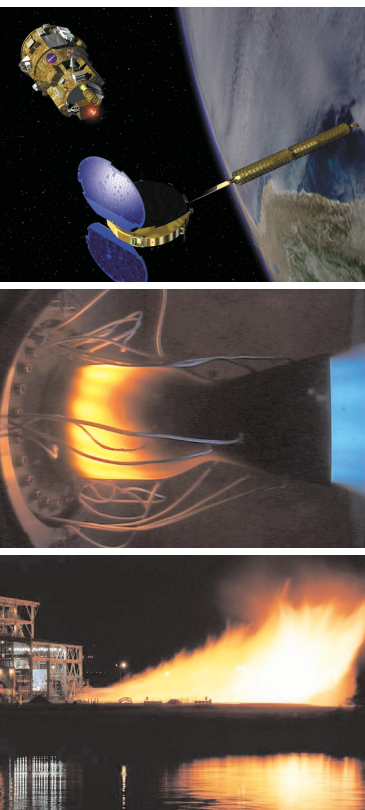
Spirals can overlap in time, with subsequent spirals beginning when progress and risk reduction are demonstrated sufficiently during the preceding spiral. For example, Spiral 1 will focus on the CEV system and robotic precursor missions. When sufficient progress is made in Spiral 1, requirements and concept definition will begin for Spiral 2, which will develop the capabilities for sustained human and human/robotic exploration on the Moon. The first successful crewed flight of the CEV, which will mark the conclusion of Spiral 1, will take place after planning activities have begun in earnest for Spiral 2. Subsequent spirals will follow a similar pattern, with an unspecified, future Spiral (which we call “Spiral N”) focusing on sustained human and human/robotic exploration of Mars.

Following a use and learn approach, spirals will build upon the capabilities developed and lessons learned in the previous spiral. As the operators use explorations systems, better ways of accomplishing on-going operations, or completely new concepts of operations will emerge. New technologies may be incorporated within a current capability so that objectives can be achieved more efficiently, or new, transformational capabilities may result from enhanced development and the application of proven technologies.

Tools for risk management, earned value management, mission simulation and cost assessment will also improve. New management tools will be employed in successive spirals in the same way other technologies will be employed to enhance future development.

By organizing our development efforts within defined spirals, we will create systems of affordable capabilities that will transform the course of exploration.





Conceptual drawing of the DART flight demonstrator rendezvousing with a target satellite; test of an engine with non-toxic propellants; test firing at SSC (top to bottom).

Certain projects derived from NASA's Orbital Space Plane and Next Generation Launch Technology Programs are also relevant and important for developing new capabilities in support of NASA's exploration agenda. These projects involve autonomous rendezvous and docking, non-toxic auxiliary propulsion, turbine power enhancements, and efficient power generation and control systems.

For example, Autonomous Rendezvous Projects undertaken by our Directorate and the Space Operations Directorate will develop and test capabilities that may be used in future in-space re-fueling and re-supply, as well as in-space repair and maintenance, and in-space assembly of modular components. We are cooperating with the Defense Advanced Research Projects Agency in efforts to improve the ability to rendezvous autonomously and dock with another orbiting body. Because of the time lag between Earth and space, Earth-based operators cannot precisely control in-space modules that are in close proximity. Thus, we will need to employ sophisticated, automated proximity operations that are self-correcting and do not depend on ground controllers during critical mission phases.

Our Auxiliary Propulsion Project will demonstrate the efficacy of new rocket systems that greatly reduce the servicing hazards now associ-

ated with the use of toxic propellants. A system of this kind would be able to operate on the lunar surface and in the harsh environment of space. Once developed, we will make the system available for application in propulsion, electrical power generation and life support systems.

The Integrated Powerhead Demonstrator Project will demonstrate the viability of hydrostatic bearings for use in advanced turbine-powered engines. Over time the bearings are expected to resist degradation, which is very important for long duration missions. In addition, new turbine materials will be resistant to hydrogen embrittlement, thereby allowing for longer operation in hydrogen rich steam without loss of material properties. Through these mechanisms, the Integrated Powerhead Demonstrator Project aims to ease assembly, rotational speed, and rotordynamic limitations now associated with rocket design.

The Power and Actuation Project will develop longer lasting and more reliable fuel cells for in flight power generation based on proton exchange membrane technology. By demonstrating electric actuation of control systems, we will seek to reduce the complexity of today's hydraulic actuation systems.



Management Rigor

Management rigor starts with the development and control of requirements. Requirements will be baselined prior to the approval of concept development. Risk must also be managed rigorously. By relying on mature technologies, risks will be minimized. Technology maturity will be assessed and will be a criterion for proceeding to detailed design and development. Technologies not developed sufficiently will be moved to subsequent spirals.

Residual risks will be identified and the risk exposure will be assessed based on the probability of occurrence and impact. The risk exposure will be reduced through funded risk mitigation projects in the highest risk areas. Schedule and funding reserves, along with sufficient technical margins, will then be allocated to bring the overall program to an acceptable level of risk.

Rigorous financial and performance management through earned value management will enable the early identification of programmatic risks by tracking cost and outcome performance on at least a monthly basis.

We will also minimize risk through rigorous, independent reviews of our programs. We will complement existing NASA safety and mission assurance and cost validation processes by conducting periodic design and development reviews that provide independent cost and technical verification of assumptions and decisions.

The level of management insight and oversight that our Capability Development programs will exercise over the development efforts will be based on





Crew members and robotic systems working together on the Martian surface (artist's concept).

Management Rigor *(continued)*

this rigorous risk assessment. Risk management will also support the identification of technologies that need to be matured for insertion into follow-on spirals.

Tools for risk management and earned value management, as well as tools for mission simulation and cost assessment, will be assessed and baselined early in the acquisition process. These management tools will be consistently applied throughout the development process.

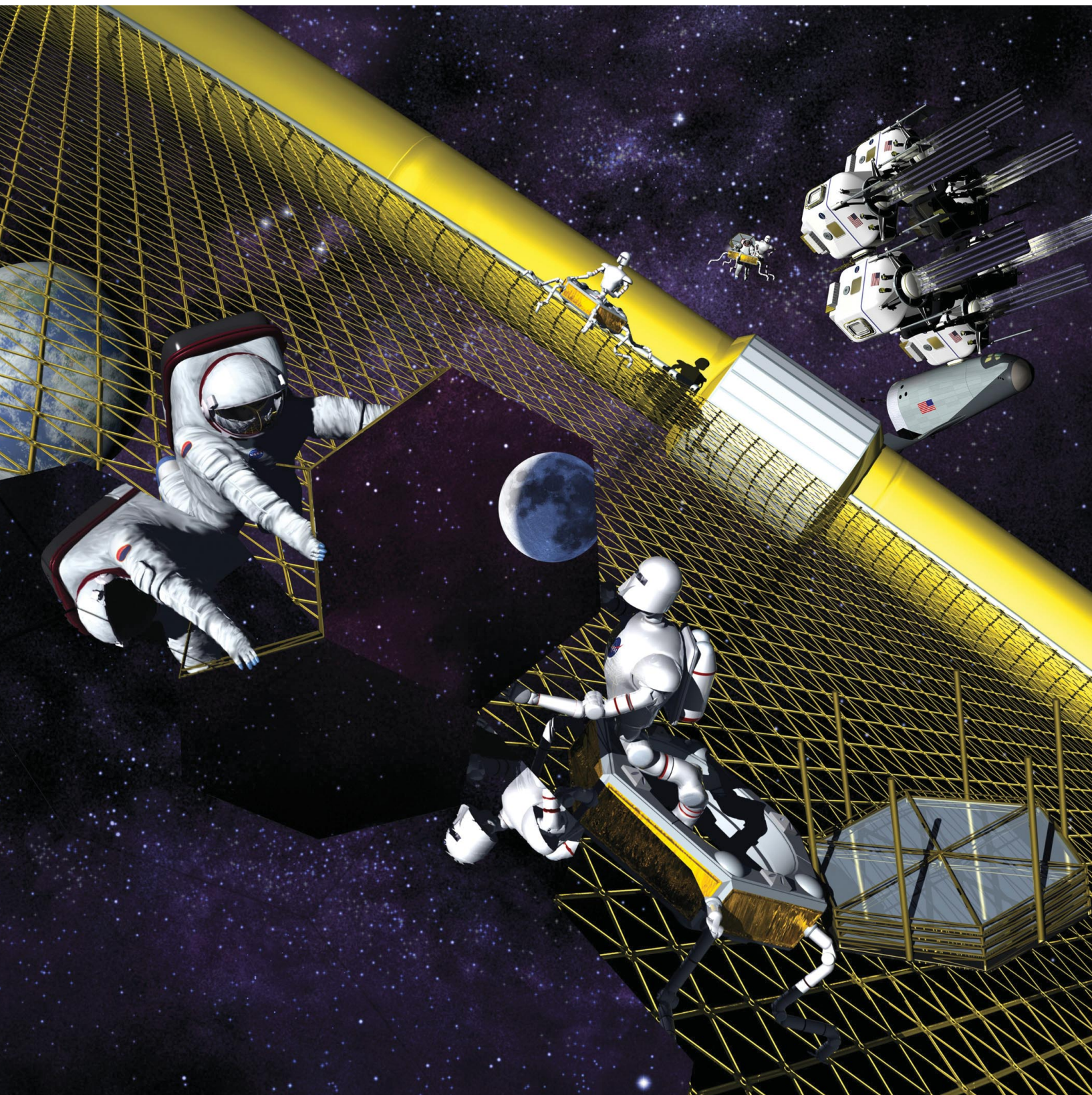
Human resource management is also essential. In order to manage a wide scope of development activity, our Directorate has sought out individuals with experience at other government agencies, other NASA Directorates, NASA Centers and industry to fill key positions. These individuals from diverse organizations will mold the best practices of many organizations to guide their respective areas in pursuit of exploration system objectives.

Our acquisition strategy depends on broad participation from all sources, with full and open competition.

We will seek innovative approaches to overall system architectures as well as advances in the various systems and subsystems that make up the constellation of exploration systems. Industrial organizations will be encouraged to team with other companies, international participants, universities, and government agencies, including the NASA Centers. Our aim is to rely on the country's best organizations, both within and outside government, including the Nation's high-technology companies and research institutions.

We will expect outstanding performance. In return, we will endeavor to provide incentives that reward excellence.





Human-robotic cooperation to construct a large space telescope (artist's concept).



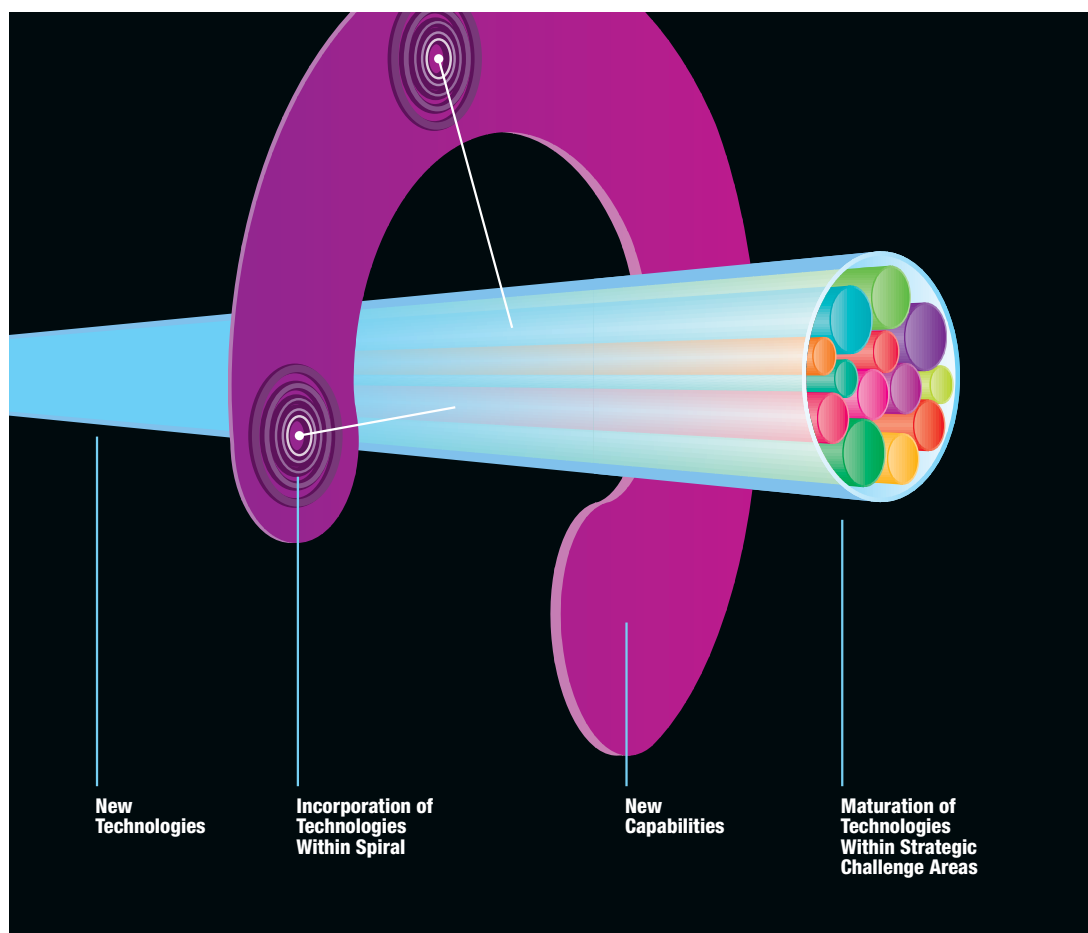
Research and Technology Development

*“It’s tough to make predictions,
especially about the future.”*

—Yogi Berra

Our aim is to create a constellation of capabilities, which enable sustained space exploration, by leveraging advanced technology to develop successive generations of more affordable, more reliable, and more effective space systems. To accomplish this, our Research and Technology Development programs will make use of some of the Nation’s best innovators to conduct a comprehensive program of research and technology development and maturation for infusion within capability development spirals.

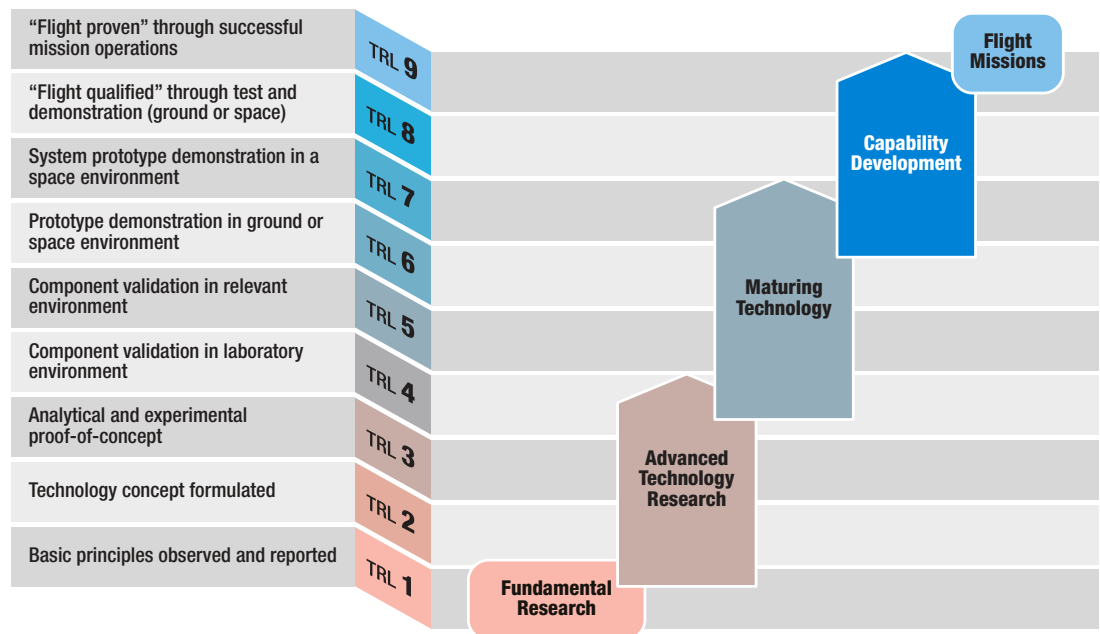
The challenge is substantial. Advances in technology represent the exploitation of known scientific fact and derive in part from new research. All of the systems within our Nation’s technological infrastructure—from cell phones to computers to automobiles to buildings—make use of scientific and technical innovation. One of our strategic aims will be to track scientific discoveries and technology achievements by other organizations, including other NASA Directorates, other governmental agencies, U.S. industry and universities, and other nations. This will allow us to determine what areas of technology innovation by others might most effectively be incorporated into our future capability development spirals. We will also be able to target our research and development efforts on those areas that are essential for NASA’s exploration agenda, while partnering with other organizations in areas of mutual interest.



We will not simply focus on new areas for technology development. We recognize it takes substantial effort to mature technologies, from the point of conceptualization to the point where they are ready for incorporation within a capability development spiral. Thus, a key aspect of our strategy will be to move essential technologies

and systems of technology from what we call a “low” Technology Readiness Level (TRL) to a “high” TRL, so that they are ready for inclusion within our Directorate’s Spiral Transformation process. For human health research and countermeasure development, we use a similar parallel process called Countermeasure Readiness Levels.

Technology Readiness Level (TRL)



Corporate Focus

We have many research and technology development programs and projects. All of them are unified by an overriding objective: to enable the Vision for Space Exploration. To ensure a unified approach, all of our technology program directors meet regularly to coordinate plans and share results. To promote a unified approach, research and development program formulation plans are approved at a high level within our Directorate. We also regularly involve colleagues from the Directorate’s Requirements, Business, and Capability Development Divisions in the review of our technology projects and programs to ensure an ongoing focus on common goals and to promote synergy.

We regularly conduct analyses to ensure that our research and development efforts are not being duplicated by other organizations, within and outside of government. Where possible we form partnerships to advance mutual interests and target our efforts on those technologies not being developed elsewhere that are essential for the future of exploration.

Our work is done in close collaboration with other NASA Directorates and NASA Field Centers. As part of the development of our formulation plans we include subject matter experts from all components of the Agency on a variety of technical teams.

We seek proposals for technology innovation from all sources, including industry, universities, and NASA Field Centers. Our broad area announcements will request proposals for both NASA-led and industry- or university-led research, both of which may involve teaming arrangements between outside experts and NASA personnel.



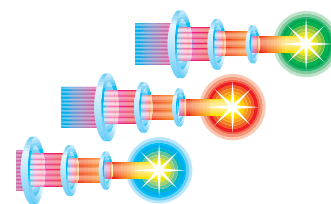
Through our investments in research and new technologies:

- We will seek to make exploration more sustainable and affordable. We will determine the viability of major systems and systems-of-systems options for longer-term future exploration systems, with the focus in the next 6–9 years on the system-of-systems level issues that will determine how we return to the Moon.
- We will address, on a priority basis, any critical gaps in needed capabilities and related technologies that emerge during the definition of the systems that our Directorate will build next—for example, to eliminate capability gaps that may exist for the first crewed flight of the CEV.
- We will develop, demonstrate, and deliver component, subsystem, or system-level technologies for consideration by system developers to reduce costs, increase safety, or provide a substantial improvement in system-level characteristics.

Our aim will be to meet these goals by continually revitalizing cycles of innovation. We will rely on the Nation's broad strengths in research and development within industry, universities and government. We will regularly and repeatedly seek ideas and contributions from all sources.

Through innovative research and technology development projects, we will tap the Nation's engines of innovation in industry, in universities, and at NASA's Field Centers. We will do this through Broad Agency Announcements that initiate competitions for new ideas at least every 3 years from both internal NASA and outside sources. Research and technology development projects will be led by those NASA Centers and those industry and university organizations best able to perform. Teaming arrangements will be encouraged. In this way, we will benefit from contributions by a diverse set of organizations, and thereby create technology improvements that are the most advantageous for our constellation of exploration systems.

Our efforts will transform the course of exploration and provide a substantial benefit to the Nation's economy. While our investments in new technologies are specifically focused on enabling more sustainable and affordable space exploration, our projects will also advance and drive the state-of-the-art in national technology areas that support our economy, including power, computing, communications, networking, robotics, materials, nanotechnology, and biotechnology. Increases in performance and reductions in cost in these areas are of great interest to industry. Through strategic partnerships that engage industry in the development of these capabilities for space exploration, we hope to



Cycles of Innovation

Corporate Focus *(continued)*

We actively seek participation by industry and by small businesses in particular, and we are eager to consider innovative arrangements that advance business interests and NASA goals. Our Centennial Challenges Program is one example of a new innovative approach to collaboration with industry. Similarly, we encourage partnership activities between our programs and other Federal agencies, such as the Defense Advanced Research Projects Agency and the National Science Foundation. Our nuclear technology program in particular depends on a close relationship with the Department of Energy, which is responsible for the safe development of nuclear reactors.

We regularly participate in international forums on research and technology development, where we share results and exchange ideas. We are actively exploring collaborations with international participants on areas of mutual interest.

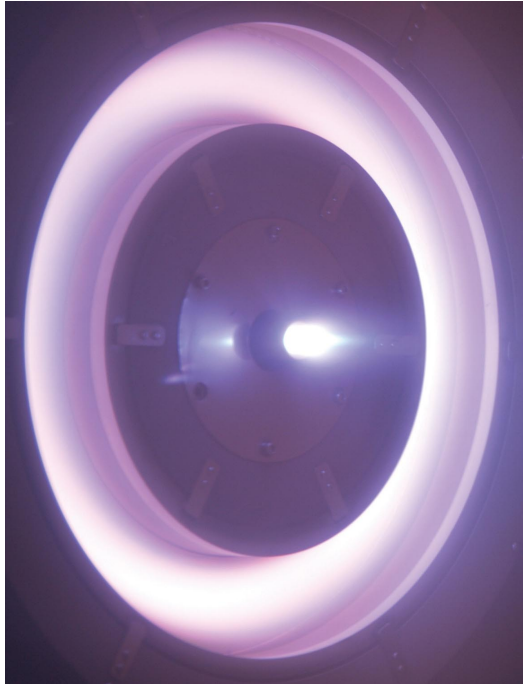
In designing our research and development portfolio we rely extensively on research targeted to enable humans to live and work in space for long duration. This includes, for example, low and mid-level TRL research for life support and extravehicular activity. The system-of-systems technologies that we develop are guided by this essential area of research. Similarly, the scientific and robotic technologies developed by the Science Directorate are essential components of the human and robotic technology portfolio that we are together creating for the Agency.



involve and inspire America's high-technology industry as well as encourage the development of new terrestrial applications.

Technology Development Based on Strategic Challenges

Starting at the conceptual level of technology development, we seek to demonstrate the validity of key ideas that may provide solutions for strategic challenges, and thereby transform the future



Hall thruster for use in electric propulsion systems

direction of technology development. To this end, our **Advanced Space Technology Program** is devoted to enhancing conceptual understandings and improving fundamental technology research at the low- to mid-TRL level. Through Broad Agency Announcements that frame intramural and extramural competitions, our Advanced Space Technology Program seeks broad participation from universities, industry and NASA Centers in wide areas of technology research. This effort is at the heart of our quest for breakthrough technologies that can revolutionize the course of exploration.

We complement our Advanced Space Technology research efforts with research funded by the **Small Business Innovation Research (SBIR) Program**. The SBIR Program actively seeks innovative ideas from small businesses throughout the country. We are refocusing the small business effort on research areas that are of importance to the future development of exploration systems. While developing new areas of research that aid in exploration, SBIR firms will also be able to refine new areas of exploration research so that they are used for commercial applications on Earth.

Advanced Space Technology research efforts that are promising will become the focus of our **Technology Maturation Program**. Through this program, we will further advance the technology-readiness levels of key technologies and seek to demonstrate that they can be effectively



Focused, Prioritized Requirements

Research and technology development activities are designed to support NASA's requirements for near-term and future space exploration missions. To do so, we focus on strategic challenge areas that can transform the future course of exploration.

These strategic challenges are designed to enable the requirements specified within the Vision for Space Exploration, including, most specifically, the directive to develop sustainable and affordable exploration systems. Accordingly, our work in research and technology development efforts will focus on mitigating the risk, reducing the cost and increasing the performance of exploration systems.

Another overarching requirement specified in the Vision for Space Exploration is to use the Moon as a testbed for future human and robotic exploration. This too will frame the evolution of technology efforts as we seek to demonstrate the viability of new technology approaches in remote locations on the lunar surface. For example, one challenge would be to enable energy-rich exploration systems for use by astronauts and robots working in areas of the Moon blocked from the Sun. This challenge could be addressed by multiple approaches, such as the deployment of surface nuclear power systems or the remote provision of power through orbiting satellites and wireless power transmission technology.

As the requirements that frame NASA's future exploration agenda are refined further, we will tailor and refine our strategic challenges and our supporting technology portfolio in support of specific exploration objectives. In a similar manner, as we demonstrate success in developing



Space Resource Utilization: A Concept for Future Space Architectures

In the future, we will develop technologies that allow us to utilize resources that are present in space. Here, an objective is to reduce the cost of space exploration by making use of in-space resources that allow us to reduce the mass—and therefore the cost—of materials that must be brought from Earth. Technologies that use lunar resources efficiently may greatly reduce the cost of providing consumable materials from Earth. Through this kind of technology innovation, we may be able to efficiently produce oxygen from lunar regolith, or create propellants by making use of hydrogen that may be trapped within the poles of the Moon. If we can produce oxygen for human consumption and propellants on the Moon, Mars, or elsewhere, we may also be improving reliability and safety, since redundant material stores would be enabled, or we may be improving the effectiveness of a space exploration activity, since it may enable longer stays on planetary surfaces.

Accordingly, one long-term goal for our technology development activities is to advance and mature technologies and systems that can extract, process, and refine materials from lunar and Martian resources. A near-term interest is to bring the technologies to a sufficiently high Technology Readiness Level so that lunar testbeds can be used to validate those technologies.

utilized in the space environment. To do so, we will integrate various component technologies into functional systems, initiate ground-based and space-based testing of promising new technologies, and evaluate and implement risk reduction strategies. Our testing and risk-reduction procedures will be both cost-effective and rigorous.

These three technology development programs—Advanced Space Technology, Small Business Innovation Research, and Technology Maturation—will focus on addressing strategic innovations that can transform our concepts for future space architecture.



Astronaut Nancy J. Currie, wearing an advanced concept space suit, participates in a test at JSC to evaluate using robots to help with in-space assembly.

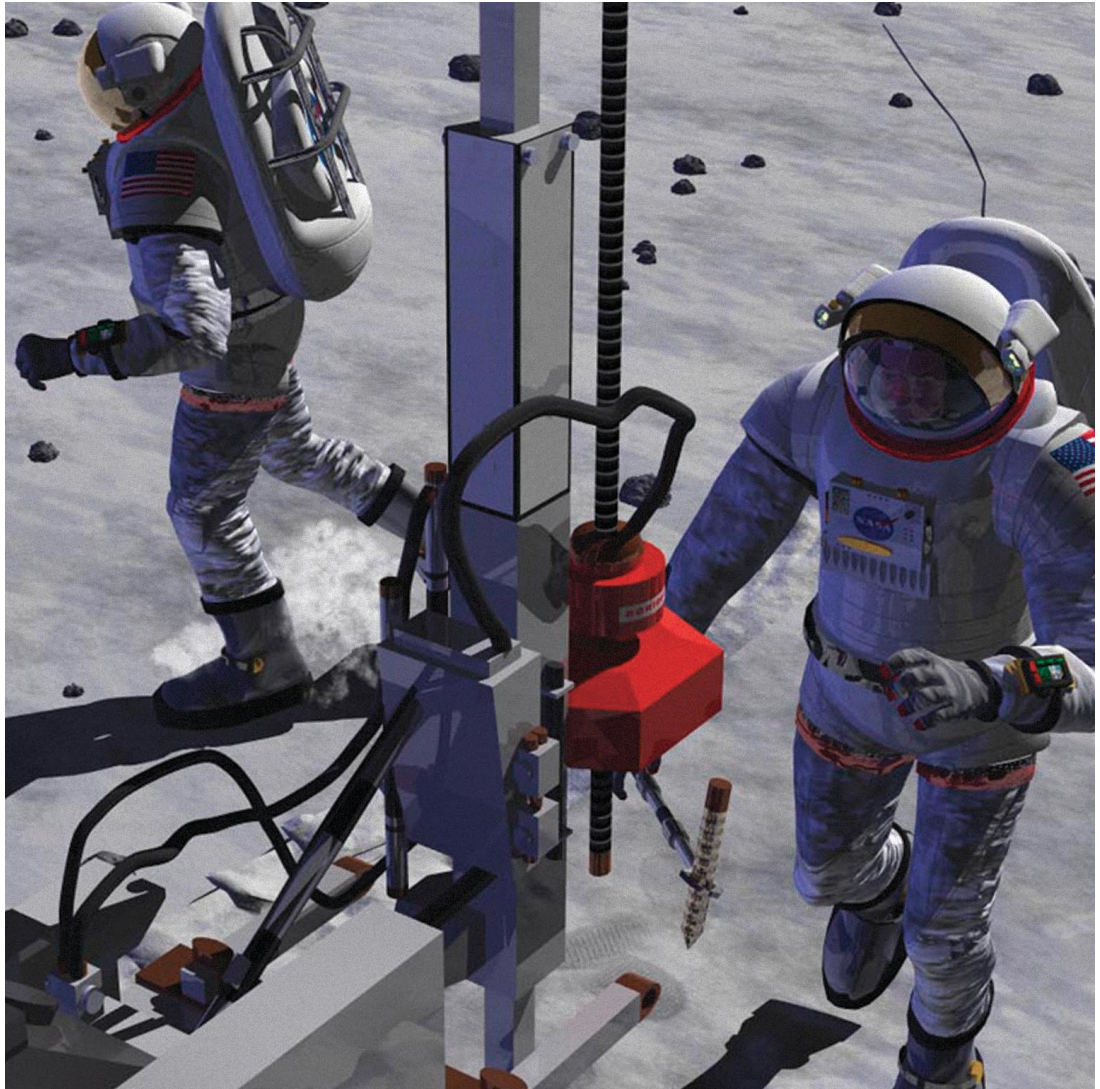
Focused, Prioritized Requirements *(continued)*

technologies that provide for greater affordability, effectiveness, or reliability within a key strategic area, like in-space use of nuclear power, those successes will enable NASA to define more robust requirements for future space missions. In this way, our Research and Technology Development Program will both respond to and influence the definition of requirements for future exploration.

We also will employ our Research and Technology Development programs to address key gaps in performance or affordability associated with near-term capability development. Thus, for example, our Requirements Division and Constellation Systems Office will specify the requirements and parameters necessary for human exploration on the Moon. This may result in a specific requirement for an advanced, flexible space suit or versatile robotic companions that an astronaut can use on the Moon to initially explore a potentially hostile environment. Similarly, our Constellation Systems Office may identify specific systems associated with the Crew Exploration Vehicle, like in-space computing or environmental control, that could benefit from increased performance. Once specific near-term requirements are defined, we will create focused research projects designed to close gaps in essential technologies. Thus, for example, we may expedite investments in enhanced space suits or initiate a technology testing and demonstration program targeted to identify those commercially available computing innovations on Earth that can perform reliably within the harsh environment of space.

The requirements formulation process will also help us prioritize our work. Our research and development investment portfolio will emphasize those strategic challenge areas and technology gap issues deemed essential for the development of specific capabilities and systems of capabilities.





Astronauts drilling
on the lunar surface
(artist's concept).

Strategic Technical Challenge Areas

Building on lessons from Apollo, the Shuttle, and the International Space Station, we must identify promising new approaches—like the use of lunar or martian resources—for sustainable human and robotic exploration and pursue the system-of-systems level innovations necessary to demonstrate the viability of those approaches.

We will design our investment portfolio to address strategic technical challenge areas where

breakthroughs would allow us to transform our space exploration capabilities. Investments in these technical challenge areas—such as in-space assembly, robotic networks, energy-rich systems, and space resource utilization—can create benefits in affordability, reliability, effectiveness, and flexibility at the component or subsystem level, at the system level, and at the system-of-systems level.



A series of 13 strategic technical challenges have been identified—representing system-of-systems issues—that are reasonably likely to be overcome through the development of new technologies. These challenges are:

- **Margins and Redundancy:** Analyzing the interrelationship between diverse subsystems, systems and systems-of-systems, particularly those that must execute mission critical operations (such as transportation or life support), with the prospect of significant improvements in the robustness in operations, reliability, and safety.
- **Reusability:** Using vehicles and systems during multiple phases of a single mission, and/or over multiple missions instead of “throwing away” crew transportation, service modules, propulsion stages, and/or excursion systems after only a single mission.
- **Modularity:** Employing common, redundant components, subsystems and/or systems that can improve reliability and support multiple vehicles, applications and/or destinations—with the potential for significant reductions in cost per kilogram.
- **Autonomy:** Making vehicles and other systems more intelligent to enable less ground support and infrastructure, including the goal of accelerating the application of commercial computing and electronics innovations within the space environment.
- **Human Presence in Deep Space:** Making it possible for humans to operate affordably and effectively in deep space and on the surfaces of moons, planets, and asteroids for sustainable periods of operations, while minimizing the risk to human life.

Modularity: A Key Strategic Technical Challenge

A key strategic technical challenge involves modularity. The International Space Station Program relies on a modular approach, assembling and integrating dozens of elements in orbit to enable the delivery of a very large platform that would otherwise not be practical to deploy in space. Like a modern personal computer, the Hubble Space Telescope employs a plug-and-play modular design that has simplified repairs and upgrades of subsystems and science instruments and has allowed the telescope to adapt flexibly to evolving mission needs, thereby enabling a significantly more valuable scientific return on investment.

Our aim for the future is to expand the use of modularity to achieve an even wider range of benefits. For example, we will investigate ways to reduce the operational cost of assembling modular space elements through faster, more efficient and reactive robotics, as well as reliable self-assembling approaches that employ autonomous rendezvous and intelligent docking mechanisms. Also, by incorporating modular elements into future space exploration systems, we should be better able to take advantage of small, commercially available launch vehicles.

With regard to operational costs, substantial life cycle cost savings across the space exploration program may be realized by using modular elements as building blocks for a multitude of missions and applications. In addition, redundantly deployed modules can enable reliability improvements by lessening the impact that would be caused by losing any single module in a system. Safety and reliability could also be enhanced by coupling modular power, propulsion, and life support systems with common reactants, propellants, and other consumables.

Modular space systems of the future need not be limited to large-scale space segments or subsystems, but could also include small electronic components. In the case of reprogrammable logic, further reliability gains can be realized by reconfiguring circuitry and recovering equivalent functionality when individual components fail. The use of modular systems with common interfaces can leverage interoperability to provide more effective end-to-end mission capabilities.

Thus, the advantages of a modular paradigm include affordability, reliability, flexibility and safety.



- **In-Space Assembly:** Docking vehicles and systems together on orbit instead of launching pre-integrated exploration missions from Earth using very heavy launch vehicles, and including in-space maintenance, servicing, reconfiguration, and evolution for exceptionally long-duration deep space operations.
- **Reconfigurability:** Deploying systems that can be reconfigured following initial deployment, to enable adaptation to new circumstances, evolution at the system-of-systems level as new elements are added, or to support high-level system options.
- **Robotic Networks:** Enabling networks of cooperating robotic systems to be deployed that can work cooperatively to extend the reach of human explorers and to prepare landing sites, habitation, and resources.
- **Logistics Pre-Positioning:** Sending spares, equipment, propellants and other consumables ahead of planned exploration missions to enable more flexible and efficient mission architectures
- **Energy-Rich Systems and Missions:** Including cost-effective generation of substantial power as well as the storage, management, and transfer of energy and fuels.
- **Space Resource Utilization:** Manufacturing propellants, other consumables, and spare parts at the destination, rather than transporting all of these from Earth.
- **Data-Rich Virtual Presence:** Locally and remotely, for both real-time and asynchronous virtual presence, to enable more robust operations and more effective science.
- **Access to Surface Targets:** Precise, reliable, repeatable, and global access to small bodies, the Moon, Mars and other destinations, including access from orbit and access from other locations on a planetary surface, through the use of advanced mobility systems.

A lunar exploration team attaching an inflatable laboratory to their lander (artist's concept, opposite page).



Spiral Transformation

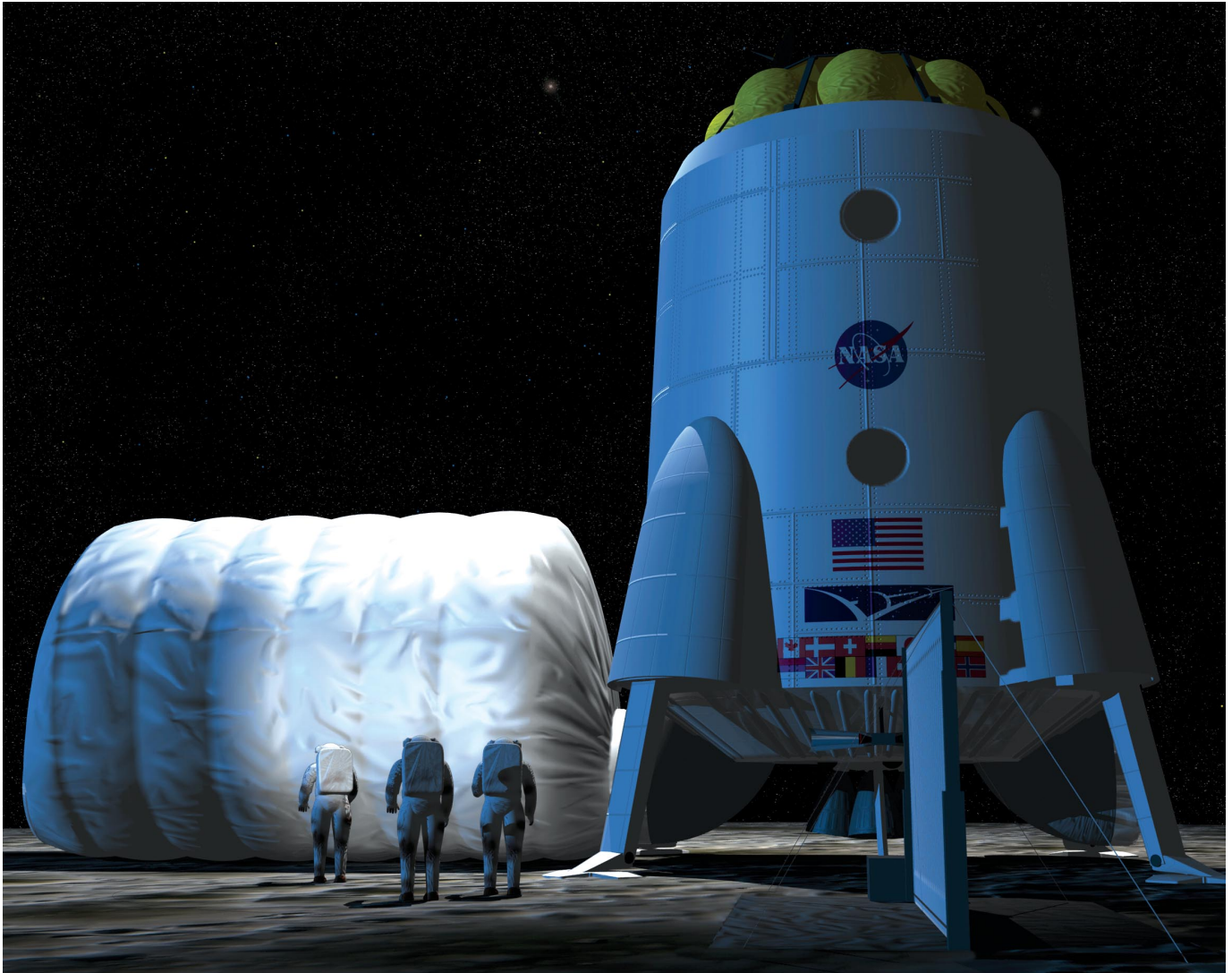
Research and technology development supports spiral transformation activities by providing the “engine” for revolutionary capability advancement. To support the development of a constellation of space exploration capabilities, research and technology development activities will be conducted in a manner that delivers new, mature technologies for each spiral of capability development.

We plan to advance and mature technologies through closely-coordinated technology development activities that are designed to bring innovative technologies to a sufficiently high Technology Readiness Level so that they can be included in the design, fabrication, and validation of individual Constellation System spirals.

Overall, technology development planning and specific technology projects will be formulated in response to the anticipated course of spiral development. Accordingly, for the first and second spiral development efforts, we will:

- Focus in the next 6–9 years on the system-of-systems-level issues that will determine how we return to and operate at the Moon.
- Address on a priority basis any critical gaps in current capability development efforts, like the development of the CEV.





Spiral Transformation *(continued)*

For each development spiral, our aim will be to provide at the outset of the spiral an array of technology choices that can realistically reduce costs, improve reliability and safety, or increase performance. As a capability is developed, we will aim to mature selected technologies in time so that they can be incorporated within the capability before deployment. This process will be facilitated by a Directorate-wide approach requiring the creation of capabilities with modular, interoperable components. Component systems may then be replaced when new technology systems are proven reliable for in-space applications.

Systems-level research and technology development also has the potential to transform the course of spiral development. In-space optical communication networks, for example, may exponentially increase data transmission volume, thereby enabling remote, virtual medical applications in times of crisis. Developments of this kind would allow humans to venture to locations for long durations in a manner that is not now deemed realistic. Within the Exploration Systems Directorate, a focused family of new systems in a wide variety of strategic challenge areas will be developed that represent critical building block capabilities for future human and robotic space exploration. Successful deployment of these new building blocks will allow NASA to adopt more robust and ambitious exploration missions in an affordable manner.



Structure for Addressing Strategic Challenges

Our technology-development efforts seek to develop solutions to strategic technology challenges. To do so, we organize our challenge-based research and development projects within specific work-breakdown structures. An illustrative structural listing follows. The specific examples may change in the future as our efforts evolve.

Advanced Space Technology Research

Advanced Studies, Concepts, and Tools

- Advanced Concepts
- Technology Systems Analysis
- Technology Databases
- System Design and Engineering Analysis Tools
- Technology Systems Verification and Validation
- Interfaces and Interface Standards

Advanced Materials and Structural Concepts

- Advanced Materials
- Structural Concepts, Dynamics, and Controls
- Mechanisms and Interconnects
- Flexible Fiber Systems
- 'Smart' Materials and Structures
- Space Environments and Effects

Communications, Computing, Electronics and Imaging

- Space Communications and Networking
- In-Space Computing and Avionics
- Ground-Based High-End Computing
- Extreme Environment Electronics
- Sensing and Imaging

Software, Intelligent Systems and Modeling

- Autonomy and Intelligence
- Crew Autonomy Interface Technologies
- Multi-Agent Teaming
- Software Engineering for Reliability
- Health Management Technologies
- Modeling, Simulation, and Visualization
- Power, Propulsion and Chemical Systems
- Energy Conversion

Power Management and Distribution

- Energy Storage
- Thermal Management
- Thermal, Electrical and Chemistry-Based Processing of Materials
- Advanced Chemical Propulsion
- Advanced Electric/Electromagnetic Propulsion
- Launch Assist and Other Novel Propulsion Concepts
- Novel Power and Transmission Technologies

Technology Maturation

High Energy Space Systems

- High-Efficiency, Low-Mass Solar Power Generation Systems
- Highly-Reliable/Autonomous Deep-Space Cryogenic Propellant Refueling Systems
- High-Efficiency/Power and Low-Mass Electromagnetic Propulsion Systems
- Deep-Throttling Multi-Use In-Space Cryogenic Engines
- Large, Low-Mass Aero-Assist Systems
- Novel High-Energy Space Systems Demonstrations

Advanced Space Platforms and Systems

- Intelligent Modular Systems
- Robust and Reconfigurable Habitation Systems
- Integrated System Health Management
- Communications Networks and Systems
- Novel Platform Systems Concept Demonstrations

Advanced Space Operations

- Space Assembly, Maintenance, and Servicing Systems
- Extravehicular Activity Systems
- Intelligent and Affordable On-Board Operations Systems
- Reliable and Responsive Ground Operations Systems
- Novel Space Operations Demonstrations

Lunar and Planetary Surface Operations

- Intelligent and Agile Surface Mobility Systems
- In Situ Resource Utilization Systems
- Surface Manufacturing and Construction Systems
- Surface Environmental Management Systems

In-Space Technology Experiments Program

- Technology Flight Experiment (TFE) Definition
- TFE Development
- TFE Integration, Launch, and Operations

Commercial Collaborations

Small Business Innovation Research

Technology Transfer and Intellectual Property Protection

- Technology Transfer Partnerships

Research Partnership Centers



In order to manage these research and development efforts, research projects that address the 13 strategic challenge areas will be initiated and organized within specific work-breakdown structures. Within each work-breakdown structure, our projects will seek to advance the Technology Readiness Level so that the technology can be applied effectively in the space environment to reduce cost or increase performance.

Focused Research and Development

Along with an approach to research and technology development that is based on strategic challenges, we will create focused research and development programs for those key areas that we now know have great potential to transform the course of exploration.

One key focus area is **human system research and technology development**. Our research ensures that the crew, a critical system for space flight, will be safe and productive during long-duration human exploration in locations far from Earth.

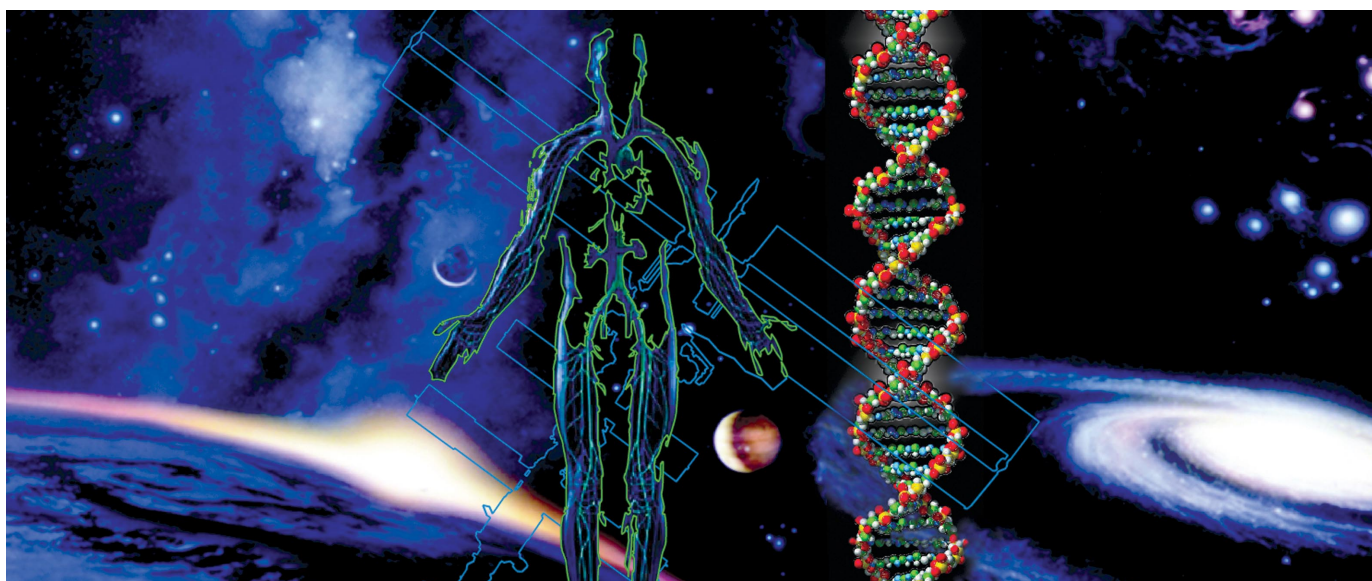
Partnerships are an integral part of our research strategy. The biomedical, biological and physical science communities, our international partners, other government agencies, research institutes, and commercial and specialized research centers participate in the entire research continuum—from understanding physiological

responses to the development and testing of new technologies, health risk countermeasures, and medical treatments.

We identify, assess, and mitigate critical health risks associated with human space exploration in a manner that involves all of our partners. These risks are documented in the Bioastronautics Critical Path Roadmap (<http://criticalpath.jsc.nasa.gov>). We also carefully consider advisory committee recommendations and National Academy of Science reports such as the Institute of Medicine's "Safe Passage" (2001).

After the return to flight of the Space Shuttle and the subsequent deployment of major research facilities, the ISS will reemerge as a platform for conducting experiments related to human health and performance and the development and testing of life support technologies. The number of crew will expand to three, and then grow to six, enabling a greater range and frequency of experiments. Countermeasures will be tested on the ISS to determine whether we can compensate for the deleterious effects of space on human physiology. Astronauts will use the ISS to practice autonomous medical care that will later be essential for future human exploration far from Earth. At the same time, the ISS will be used to evaluate the performance in microgravity of selected new components, subsystems, and systems necessary for advanced life support.

Mosaic portraying human system research.





The ISS flies over the Bahamas, as viewed by the crew of STS-108 (above). Astronaut Edward Lu exercises on the Cycle Ergometer and Vibration System on the ISS (below).



Ongoing research efforts on the ISS and other research platforms will be enhanced in order to assure the health, safety, and performance of crews on exploration missions. Examples of these research efforts follow.

Research Focus: Crew Health

As the boundaries of human space flight are expanded, the need for autonomous performance by the crew and their medical care systems becomes increasingly important. The pathway to autonomy requires a systematic approach to develop the capacity to provide medical care and perform research with less input from people on Earth. The primary challenge is to ensure that the necessary medical procedures, tools, systems, and training are developed to support missions of increasing duration and distance from Earth.

Crewmembers in space can experience many of the medical problems that individuals experience on Earth, including illness and accidents. In addition, microgravity sets in motion a range of physiological responses that are not necessarily problematic during space flight, but potentially risky upon return to a gravitational environment or during extravehicular activity. Other hazards are environmental in nature and include exposure of the crew to space radiation and contamination of the spacecraft and its life-support systems.



Safe tolerance limits and operating bands must be established for the crew during the mission. This includes setting mission-specific and lifetime health standards that protect astronauts from any adverse biomedical effects caused by space flight.

Our research strategy for assuring human health and performance will invoke outcome-driven, product-oriented experimentation in humans, animal models, and cell-based systems, using the most advanced approaches in biomedical research. For example, for loss of bone-mass density and muscle strength, we will:

- Conduct ground- and flight-based research to develop countermeasures to prevent or minimize microgravity-induced acceleration of osteoporosis and bone loss, changes in bone quality, and formation of renal stones
- Develop new predictive strategies and assessment tools for early detection of osteoporosis
- Develop strategies to enhance fracture repair and bone strength, increase resistance and decrease susceptibility to fracture, and understand regional bone growth

For muscle alterations and atrophy, we will:

- Design and develop countermeasures (both ground- and flight-based) to minimize muscle atrophy and increase muscle strength and endurance using combinations of aerobic and resistive exercise, pharmacological therapies, and artificial gravity.

Other prime areas of concern include behavioral health, cardiovascular systems, and immunological response.

Research Focus: Radiation

Radiation exposure will be limited according to the highest ethical standards and best practices for radiation protection. Space radiation poses special risks to crew health and safety during a mission and also has clinically relevant implications for crew life expectancy. Space radiation differs substantially from the radiation environment on Earth, and consists mainly of high-energy protons and atomic nuclei of the heavier elements.



The Phantom Torso is used on the ISS to detect and measure neutron radiation (above). A radiation beam line is used to gather data on effects from exposure to high-energy particles (left).

The results of research on radiation are targeted to allow crewmembers to participate in long-duration missions beyond low-Earth orbit. Near-term research targets and products will:

- Establish acceptable levels of risk to crew health associated with space radiation exposure
- Characterize and mitigate lunar radiation environment using data from the Lunar Robotic Orbiter
- Incorporate advances in the calculation and measurement of multifunctional material shielding properties into CEV design
- Implement an ongoing assessment of radiation risk management status, and improve the models used to predict radiation levels and effects
- Develop and determine implementation strategies for operational countermeasures including shielding, dosimetry, crew selection, nutritional supplements, and pharmacological intervention





The 20-G Centrifuge, used for hypergravity research at the Center for Gravitational Biology Research.

Research Focus: Advanced Life Support

Exploring beyond low-Earth orbit and making use of resources discovered in new environments require the basic tools already developed on Earth for energy production and the recycling of essential life-support components, such as air and water. These basic tools have been developed and optimized on Earth, but biological and physical processes often perform quite differently in reduced-gravity environments. Over the next 10–15 years, the enabling knowledge and technology base will be built for exporting

the technology processes developed on Earth to new, reduced-gravity environments.

The primary challenge for life-support systems is to move from largely open systems that require frequent resupply to closed systems that recycle air, water, and waste. It is also important to reduce the size and complexity of life support systems with a thorough understanding of sensitivity to gravity, multiphase flow, microbial dynamics, and heat and mass transport processes. The resulting systems must require less power than

Structure for Addressing Bioastronautics Research

Human system research and technology development efforts are organized within the following areas:

Crew Health and Performance

- Human Health Countermeasures
- Behavioral Health and Performance
- Autonomous Medical Care

Radiation Health

- Radiation Exposure and Mission Requirements
- Measurement Technologies
- Shielding Solutions
- Risk Assessment and Projection
- Biological Countermeasures
- Life Beyond Low-Earth Orbit

Human Support Systems

- Advanced Life Support
- Extravehicular Activities Technologies
- Space/Human Factors Engineering
- Advanced Environmental Monitoring and Control
- Contingency Response Technologies
- ISRU for Human Support Technologies
- Advanced Integrated Matrix
- Low-Gravity and Exploration Research



current systems, be highly reliable and autonomous, and be physically smaller than current systems.

Another challenge is to develop advanced extravehicular activity systems, including a protective suit optimized for use on planetary surfaces. It will be critical to develop portable life-support systems for extravehicular activity that save consumables and meet requirements for carbon dioxide, humidity, and trace contaminant removal, with regenerable closed-loop thermal control, passive and active radiation shielding, and monitoring capabilities.

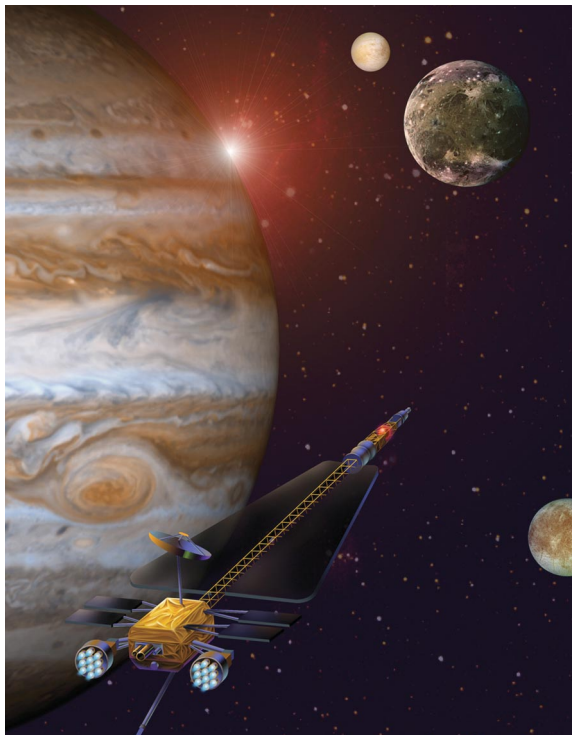
Research and technology development targets in the near-term include:

- Developing reliable, lower system-mass air revitalization, water recovery, food production and processing, waste processing, and resource recovery systems
- Developing miniaturized sensors and autonomous control systems to monitor the internal environment and increase the robustness and efficacy of life support systems
- Developing models and conducting flight experiments to validate multiphase flow and thermal-management technologies needed for new life-support systems
- Performing on-orbit validation of critical life-support technologies or relevant components to certify them as candidate technologies for missions beyond low-Earth orbit
- Developing and testing advanced extravehicular activity components and systems

Using EVA life support, astronaut John B. Herrington works on the Port One truss of the ISS.



A nuclear-propelled spacecraft approaching Jupiter's moon Europa (artist's concept).



Another area of research that can transform the future course of exploration is **nuclear technology development and demonstration**. Currently, available power constrains NASA's space missions. More power would allow for longer and more effective scientific exploration, more maneuverability at destinations, in some cases reduced travel time to destinations, and a more substantial communication link between Earth and the exploration spacecraft. For this reason NASA has initiated a research and development effort focusing on in-space use of nuclear power.

Our nuclear systems program, "Project Prometheus," is cooperatively undertaken with the Department of Energy, which is responsible for the safe development of all nuclear systems used by the United States, including the nuclear systems we are developing and those used by the Nation's ships and submarines.

Our nuclear research efforts concentrate on two types of space nuclear power systems: radioisotope and fission, which differ in the process by which heat is produced. We are developing new radioisotope power systems that could potentially operate in the vacuum of space or on planetary bodies and significantly increase the efficiency with which heat from the radioisotope is converted to electricity.

Research Focus: Fission Power Systems

We will also focus on the design and development of fission power systems that would offer great advantages over current power systems. Fission reactors could provide spacecraft with thousands to hundreds-of-thousands of watts over the course of many years, safely and reliably. Exploration missions would be able to use these space reactor systems to provide large amounts of power for extended periods, regardless of distance or orientation to the Sun, thus creating a new paradigm in robotic and human exploration. Safety will be a primary driver in every aspect of the program, including space-



Management Rigor

While technological forecasting is inherently a challenging activity because of the uncertainties, this does not mean that technology development projects cannot be managed so that investigations are accomplished on a predictable schedule or within budgeted costs. Rather, like other types of projects, technology development activities are more likely to be completed on-schedule and on-cost when they are well-planned and well-executed.

We intend to select and manage projects that provide the best potential for greatly improving the sustainability of space exploration activities. We will do this by rigorously evaluating potential technologies, making sure that the organizations we choose to develop them are competent and prepared for these projects, and by tracking and controlling the projects to ensure that they remain on schedule and within cost constraints. As disciplined managers, we will employ proven tools like earned value management. We will review our projects rigorously at key milestones, and we will require independent reviews of cost, performance, and risk management.

This does not mean that there will not be surprises. When the surprises are beneficial, that is, when they result in systems that are better than we had anticipated, we intend to exploit the results fully. But, when the surprises are negative, we intend to rapidly factor the results into our management planning—redirecting projects where necessary and halting projects when that is the appropriate response.

One part of our effort will be to ensure that technology-development projects are thoroughly considered prior to their initiation. We intend to make use of competitive procurements in order to ensure that we provide opportunities for the best technologies and projects to be identified.



craft design, testing, manufacture, and operation. A hierarchy of safety objectives, requirements, and engineering specifications would be established and followed during every phase of the mission.

These evolving power systems will enable increasingly bold exploration and science. At present, NASA is studying a mission to conduct close-range, extended investigations of the icy moons of Jupiter: Callisto, Ganymede, and Europa. These investigations, designed to search for water, energy, and the chemical precursors to life, would be specifically enabled by the high power and long life of the nuclear technologies.

At present, we are pushing the limits of solar power and chemical propulsion technologies to support exploration of the Solar System and beyond. Although NASA continues to invest in the development of these technologies, we do not expect them to meet the requirements of many future mission concepts, including the proposed mission to Jupiter's icy moons. Prometheus-developed power systems would enable this spacecraft to use instruments of much greater sensitivity and resolution than those carried on previous or current missions to distant planets. Examples of these instruments are high-power radars that would penetrate deep into the subsurface of planets and moons, more-capable cameras and spectrometers with greater

resolution to map entire moons, and instruments that use lasers to measure topography or even illuminate planetary surfaces.

Another revolutionary capability enabled by space nuclear reactor power would be the ability of the spacecraft to maneuver into close-range, optimized orbits of planetary bodies and to make mid-course changes in the mission in response to real-time discoveries. Evolved maneuverability would result from propelling the spacecraft with extremely fuel-efficient ion thrusters, which would be powered by the space reactor. The availability of substantial on-board power would also allow for massive amounts of data to be sent back to Earth at rates never before possible from such great distances.

Once proven for in-space use, these new nuclear systems may also be used to supply power, and perhaps propulsion, for extended human and robotic operations on the Moon, and eventually on Mars. In this way, the enabling capabilities of safe and reliable nuclear systems would transform the course of future human and robotic exploration.

In developing nuclear technologies, NASA and the Department of Energy will collaborate with experts in industry. All program activities will be conducted in as transparent a manner as possible, and we will provide numerous opportunities for public participation throughout the life of the program.

Management Rigor *(continued)*

When evaluating competitive approaches, we will make use of a set of key questions, borrowed from the Defense Advanced Research Projects Agency, which are:

- What is the technology (and project) trying to accomplish?
- How is the function performed today and what are the limitations?
- What is truly new about the proposed approach that will remove current limitations and improve performance?
- If successful, what difference will it make and to whom?
- What are the mid-term exams, final exams, or full-scale applications required to prove the hypothesis? When will they be done?
- What is NASA's exit strategy? How will the technology be turned into a new capability or a real product?
- How much will it cost?

Our human and robotic technology projects will follow a new, standard template that allows a more effective integration of innovation with the development spirals for future systems. We will seek to continually revitalize the process of challenge-driven technology development. Our aim will be to repeatedly seek ideas and contributions from a broad set of sources in industry, government, and universities. We will do this by initiating competitions for new ideas within cycles of innovation. Our aim will be to cycle our broad area announcements at least every 3 years, and in this way regularly and repeatedly seek new ideas and contributions from intramural and extramural sources.



Impression of NASA scientists developing technologies that detect spores and bacteria.



Novel Modes of Participation

Along with focusing our research efforts on strategic challenges, we have created programs that seek to spark innovation by creating novel modes of interaction between government, industry, and universities. Through innovative partnerships, we can both advance space exploration and provide opportunities for commerce on Earth and between Earth and space.

Our **Innovative Technology Transfer Partnerships** are an important tool for advancing the Nation's economic interests, as mandated in the Vision for Space Exploration. These partnership efforts utilize flexibilities that are inherent in the Space Act of 1958 to create novel partnership agreements between private-sector companies and NASA that advance both NASA's exploration goals and business interests. The agreements often involve the licensing of NASA's intellectual property rights, an exchange of technical expertise, and the sharing of technological results.

As an example, our Directorate has a technology exchange agreement, and a related patent license agreement, with a company that is seeking to develop inflatable, flexible products for sale in the marketplace. We are interested in inflatable technologies for future in-space use, as inflatable materials may allow us to launch more volume for less weight than a rigid structure. In addition, certain flexible materials may provide greater protection against micro-meteor debris and greater protection against in-space radiation than the inflexible material that is currently used in space.

To facilitate the creation of innovative commercial partnerships, we provide industry and public access to the TechFinder database, which features approximately 18,000 updated and evolving NASA technologies, as well as accompanying technical briefs. Publications that we widely distribute also describe these technologies, which are available for licensing to U.S. companies. Technology transfer and intellectual property experts help industry learn about and use NASA technologies, and help NASA utilize technology innovations created by others. Along with national and regional technology transfer centers that coordinate the exchange of technologies between NASA and industry, our small business programs support technology transfer between NASA, small businesses, and universities. Through these efforts, industry can achieve business goals while working together with NASA to overcome technical challenges that are important for the Nation's economy and exploration agenda.

Research Partnership Centers are consortia of government, industry, and university researchers that contribute to technology challenges common to both NASA and industry. Currently, Center research focus areas include in-space testing, power, propulsion, materials, in-situ resource utilization, imaging, communications, electronics, medical technologies, biotechnology, radiation mitigation, robotics, and sensors.



NASA's investment in the Research Partnership Centers is highly leveraged through contributions by industry and university partners. Partners invest in maturing technologies that benefit both exploration and industry, thereby reducing NASA's cost and risk while at the same time invigorating American industry. Due to the quick response time needed by industry partners, Center research projects are typically of short duration.

In addition, **University Research, Engineering, and Technology Institutes** were established to strengthen NASA's ties to universities through long-term, sustained investment in innovative and long-range exploration methodologies critical to NASA's future. The institutes support technology- and capability-development efforts associated with propulsion systems, structures, vehicle health management, and systems design. We aim to use the institutes to enhance and broaden university involvement in our programs.



Astronauts exploring the Martian terrain (artist's concept).



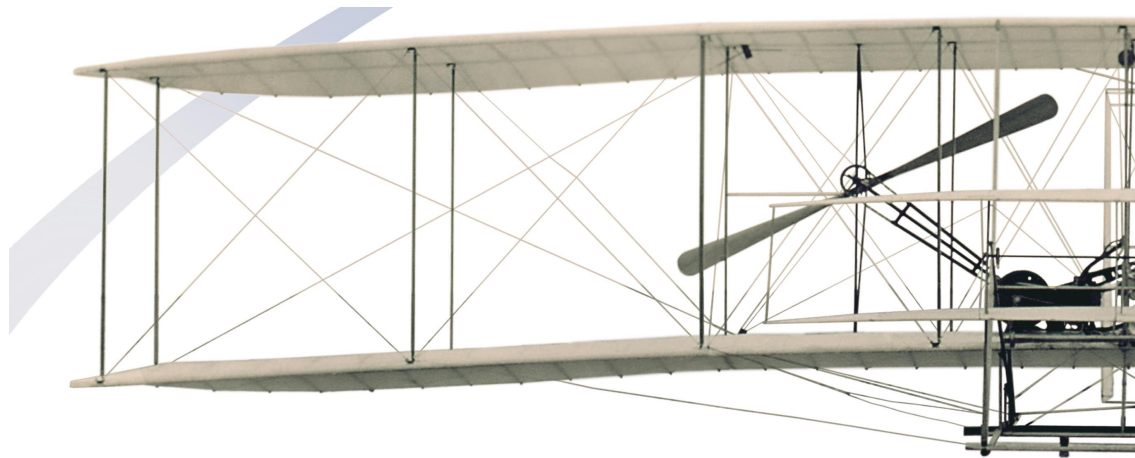
The road to innovation is unpredictable and circuitous. While advancing humanity's exploration goals requires a steady improvement in existing technologies, it also demands that we open our minds to creative solutions. Through our **Centennial Challenges Program**, we will initiate prize contests to stimulate innovation through competition. By making awards based on actual achievements that advance the NASA Mission instead of unproven proposals, Centennial Challenges seeks novel solutions to NASA's mission challenges from non-traditional sources of innovation in industry, universities, and the public.

As an additional way to harness the energy and creativity of U.S. industry, universities, and other

organizations, our Directorate will establish annual prizes that reward innovation in three areas that are vital to realizing the Vision for Space Exploration:

- Revolutionary advances in fundamental technologies
- Breakthrough robotic capabilities
- Very-low-cost space missions

Specific areas for prize competition will be defined through an inclusive process. Internal NASA analyses will be used to identify potential areas that are most suitable for this form of competition. Based on those initial analyses, we will



100 YEARS

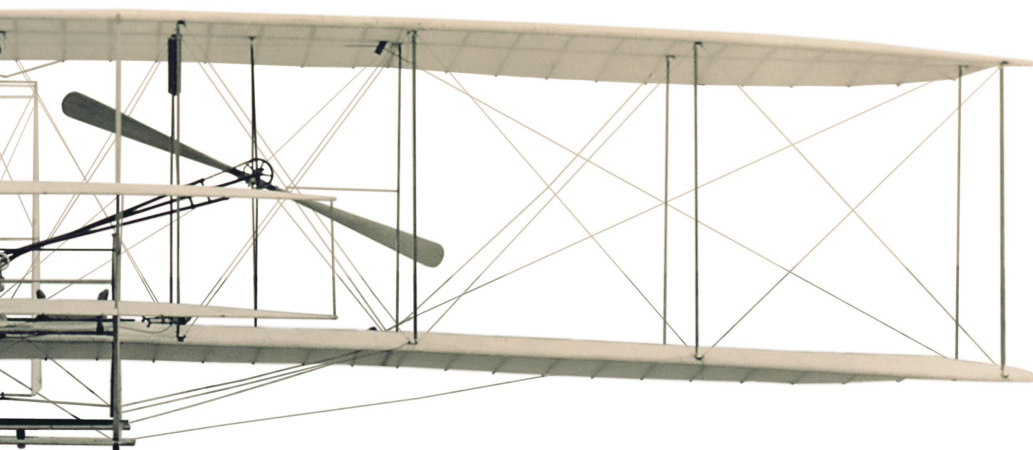


sponsor workshops to seek suggestions from organizations and individuals outside NASA and to refine ideas. On this basis, we will define areas for prize competitions and specify levels of achievement associated with each prize. We will cycle through this process again when defining new prize areas and new levels of achievement.

We designed the Centennial Challenges program to stimulate innovation in ways that the normal federal procurement procedures cannot. Winners of Centennial Challenge prizes will not only provide solutions that address gaps in current technologies, they will be free to frame their efforts in a way that maximizes their return on investment.

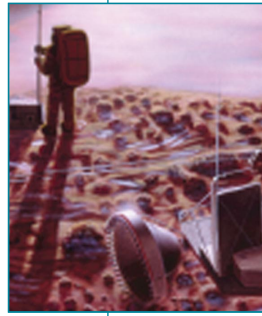
We also hope that the Centennial Challenges effort will enrich NASA research by involving communities and organizations that are new to NASA. As these competitions unfold, we will share them with the public. In this way, we will endeavor to educate, inspire, and motivate all interested Americans.

How can people and organizations become involved? Interested parties can obtain information about workshops and prizes through the internet at www.centennialchallenges.nasa.gov. We will achieve our exploration goals with focus, drive, intelligence, and creativity. Any organization or individual who shares these qualities can rise to and meet one or more of our Centennial challenges.



OF FLIGHT





4

Beyond the Horizon



Human travelers on the surface of Mars; the area depicted is Noctis Labyrinthus in the Valles Marineris system of enormous canyons (artist's concept).



4 Beyond the Horizon

Over the course of the next 50 years, we envision a constellation of new capabilities that is well managed, cost effective, and ever growing. The constellation of capabilities will be revolutionary and will comprise an international space infrastructure that will reach the outer planets.

“Man, in his quest for knowledge and progress, is determined and cannot be deterred. The exploration of space will go ahead...it is one of the great adventures of all time...”

—President John F. Kennedy

We do not know what the future will bring, but we are sure that groundbreaking developments will occur. During this time, we envision campaigns of human/robotic exploration that will catalyze new discovery and understanding, inspire the next generation of explorers, lead to peaceful exploration of the Solar System by all nations, spark commerce between Earth and space, invigorate America’s high-technology industry, and benefit life on Earth.

We envision creating capabilities for sustained human exploration on Mars and beyond, revolutionary new space telescopes that will reveal Earth-like planets around other solar systems, and robust missions to the icy moons of Jupiter and to Titan, a moon of Saturn with an atmosphere similar to that of ancient Earth.

The people who will engage in this future exploration are just now learning about the Solar System in school.

Our children’s future is just beginning. We feel privileged to work for them and their children’s children.







Appendices

Appendix 1: Agencywide Requirements

NASA has developed overarching “Level-0” requirements for human and robotic exploration, derived from the Vision for Space Exploration. The Level-0 requirements are:

- 1.0 NASA shall implement a safe, sustained, and affordable human and robotic exploration program to extend a human presence across the Solar System and beyond.
 - 1.1 NASA shall develop the innovative technologies, knowledge, capabilities, and infrastructures to support human and robotic exploration.
 - 1.2 NASA shall conduct a series of robotic missions to the Moon to prepare for and support future human exploration activities.
 - 1.3 NASA shall conduct human lunar expeditions to further science, and to develop and test new exploration approaches, technologies, and systems, including the use of lunar and other space resources to support sustained human space exploration to Mars and other destinations.
 - 1.4 NASA shall conduct robotic exploration of Mars to search for evidence of life, to understand the history of the Solar System, and to prepare for future human exploration.
 - 1.5 NASA shall conduct human expeditions to Mars to extend the search for life and expand the frontiers of human exploration, after successfully demonstrating human exploration missions to the Moon.
 - 1.6 NASA shall conduct robotic exploration across the Solar System for scientific purposes and to support human exploration.
 - 1.7 NASA shall conduct advanced telescope searches for Earth-like planets and habitable environments around other stars.
- 2.0 NASA shall acquire an exploration transportation system to support the delivery of crew and cargo from the surface of the Earth to exploration destinations and the safe return of the crew to Earth.
- 3.0 NASA shall complete the assembly of the International Space Station, including the U.S. components that support U.S. space exploration goals and components provided by foreign partners (planned by the end of the decade).
 - 3.1 NASA shall focus the use of the Space Shuttle to complete assembly of the International Space Station.
 - 3.2 NASA shall focus U.S. International Space Station research and technology on supporting space exploration goals.
 - 3.3 NASA shall separate transportation of crew and cargo to the International Space Station to the maximum extent practical.
- 4.0 NASA shall pursue opportunities for international participation to support U.S. space exploration goals.
- 5.0 NASA shall pursue commercial opportunities for providing transportation and other services supporting the International Space Station and exploration missions beyond low Earth orbit.
- 6.0 NASA shall identify and implement opportunities within missions for the specific purpose of inspiring the Nation.

Appendix 2: Acronym List

BAA	Broad Agency Announcement	JSC	Johnson Space Center
CEV	Crew Exploration Vehicle	MSFC	Marshall Space Flight Center
CRL	Countermeasure Readiness Levels	NASA	National Aeronautics and Space Administration
DART	Demonstration of Autonomous Rendezvous Technology	RFI	Request for Information
EELV	Evolved Expendable Launch Vehicle	RFP	Request for Proposal
EVA	Extravehicular Activity	SBIR	Small Business Innovation Research
ISRU	In Space Resource Utilization	SSC	Stennis Space Center
ISS	International Space Station	STS	Space Transportation System
		TRL	Technology Readiness Level

Appendix 3: Artist's Credits

Dennis Davidson	Page 10	Pat Rawlings	Pages 38, 39, 46, 65
John Frassanito and Associates	Pages 3, 28, 52, 55	Tietronix Software Inc.	Page 7
John Lowery	Page 36		



Appendix 4: Internet Links

Bioastronautics Critical Path Roadmap

<http://criticalpath.jsc.nasa.gov>

Centennial Challenge Program

<http://centennialchallenges.nasa.gov>

Columbia Accident Investigation Board

<http://history.nasa.gov/columbia/CAIB.html>

Exploration Systems Mission Directorate

<http://exploration.nasa.gov>

National Aeronautics and Space Administration

<http://www.nasa.gov>

National Aeronautics and Space Administration Strategic Plan

http://ifmp.nasa.gov/codeb/docs/2003_Strategic_Plan.pdf

Nuclear Technology and Demonstration

<http://exploration.nasa.gov/proprom.html>

Office of Biological and Physical Research

<http://spaceresearch.nasa.gov>

President's Commission on Implementing the Vision
for Space Exploration

http://www.nasa.gov/pdf/60736main_M2M_report_small.pdf

President's Management Agenda

<http://www.hq.nasa.gov/codea/pma>

Space Act—1958 Congressional Legislation

<http://www.hq.nasa.gov/ogc/spaceact.html>

Small Business Innovation Research Program

<http://www.sbir.nasa.gov>

TechFinder Database

<http://technology.nasa.gov/>

Vision for Space Exploration

http://www.nasa.gov/missions/solarsystem/explore_main.html

Exploration Systems Strategy Working Group

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draft 2.1





Held by surface tension, water sits atop a pea plant on the ISS. Water systems in space must be adapted to microgravity fluid mechanisms.



For more information regarding the work of the
Exploration Systems Mission Directorate, please visit our Web site
<http://exploration.nasa.gov>



The background is the Helix nebula as observed through Hubble.



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